A State of the Art Report of CAD/CAM/CIM Systems Technologies for the U.S. Shipbuilding Industry

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Table of Contents

List of Figures

I. Introduction

The purpose of this report is to review the current state of systems technologies as they relate to shipbuilding production processes. The focus is on the areas of computer-aided manufacturing (CAM), numerical control (NC), and enterprise resource planning (ERP). However, the report also addresses the areas of computer-aided-design (CAD) and product data management (PDM). Although these latter areas are more appropriately in the design and engineering realm, the information created in these systems provides the foundation for many production processes. Some potential improvements in production process rely heavily on changes or enhancements in the design systems. Moreover, this report emphasizes shipbuilding specific requirements, system capabilities and opportunities. Systems technology support for the shipbuilding industry is built largely on top of systems that have been developed in support of the requirements of other industries. One of the challenges is to understand where those other requirements coincide with shipbuilding requirements and where they diverge. With such an understanding it is possible to plan when to let other industries drive systems technology and to identify those areas where the shipbuilding industry needs to be more proactive.

Previous research has been done in this area in recent years. In 2001 NSRP published an industry report, *Benchmarking of U.S. Shipyards*. In 1997 NSRP published an Evaluation of Shipbuilding CAD/CAM/CIM Systems. Phase I of the report was an evaluation of existing systems (NSRP 0476) and Phase II was requirements for future systems (NSRP 0479). There has been considerable activity in the past five years, and a second look at current CAD/CAM/CIM capabilities is timely. The NSRP Benchmarking report did not address systems technology directly, but it did define a set of best practices, largely production processes, and ranked U.S. shipyards against overseas competition. The ranking indicated those process areas in which there was room for improvement. The results of the Benchmarking study have been used to identify the process areas that are addressed in the current report. This report, while organized around best practices themes, does not attempt to rank individual shipyards, but rather it describes the state of the art, of systems technology, as it applies to each of those themes. The Benchmarking report concluded that although US shipbuilders were improving in productivity, so was the competition. The recommendation was that the typical medium or large shipyard should seek a 75% improvement in productivity over the next five years. The report further concluded that because US shipyards have a high cost base, there needs to be a deliberate effort to offset that disadvantage, and that that could be accomplished by means of advances in systems technologies.

The Benchmarking report also contained a number of specific findings in each of the best practices themes. One area that was highlighted was accuracy control. Accuracy control is essential for error-free manufacturing, yet it is not well supported in US shipyards. The costs associated with poor performance in this area are far-reaching. Low scores in the erection and fairing best practice area were specifically attributed to this shortfall. Another best practice theme that scored low was outfitting. The conclusion was that there needs to be better means for delivering more appropriate technical data. In addition, U.S. yards could benefit from more effective design for production. The report recommended the formalizing of the shipyard's build strategy. These recommendations argue for more effective management and use of manufacturing and related data.

The CAD/CAM/CIM evaluation report described the CAD/CAM/CIM systems that were in place at the time (1997) at several overseas shipyards. The report provided a detailed description of the deployments at each yard, including such items as the network infrastructure, operating systems, and databases in place at the time. Of course, the focus was on which CAD and CAM systems had been implemented. The report also described the degree of customization that had been done as well as the circumstances under which the customization was accomplished. One of the objectives of the report was to assess which functional capabilities were being supported by systems technology. The report also included a paper evaluation of the CAD/CAM software packages that were being used at the shipyards.

The CAD/CAM/CIM evaluation re-iterates a position with respect to systems technologies, which is generally accepted as a truism among shipbuilders. The position is that systems technologies are secondary to business processes. "A major finding relates to the reasons behind use of technology. As previously stated, the companies assessed had adopted aggressive business practices. Further, the use of technology was not pursued for its own sake, but as an enabler to achieve the business objective." A statement like this seems harmless enough, but it reveals an attitude toward systems technology that has hampered the progress that could have otherwise been made. The implication is that system technologists are pushing technology for their own ends. There is often an uneasy relationship between system-oriented and process-oriented personnel at the shipyards, even within the IT organizations. The process-oriented group wants to give the impression that the only real successes occur when the technology is "pulled" by them rather than "pushed" by the technologists. It is not unusual for deployments of new technology to fail, but the reasons for these failures are usually complex and far-reaching, sometimes involving incidental such as the experience of the developers and sometimes involving deeper issues such as misunderstanding of technical capabilities and limitations. Sometimes the reasons are not technical at all, but are related to resistance to change. In any case, it is rare to find a shipyard that is willing to invest resources in technology for technology sake. This controversy hides a key issue: at shipyards today there is a lack of detailed knowledge of the capabilities and limitations of systems technologies. At the management level there is little opportunity to devote the effort required to make sound technical judgments, but even at the IT level there are issues. Since most shipyards have adopted a policy of outsourcing systems technology support, systems technology expertise has gradually migrated out of the shipyards. This is in contrast to the situation in the 1970s and 1980s when the larger shipyards used their own engineering staffs to develop the first generation CAE and CAD applications. The problem with this situation is that, in fact, technology does not respond to process drivers. On the contrary, the most innovative and revolutionary process improvements come only after new breakthroughs in systems technologies.

The CAD/CAM/CIM evaluation report also says that the shipyards that were most successful had a well-defined business and technology plan (including a plan for sustaining research and development activities). This was the case in the 1990s when the direction at the shipyards was clear: migrate the CAD and solid modeling so that product data could be captured once and re-used many times. The strength of this strategy was that it was concise and easily understood by everyone involved. Today the situation is more challenging. The key technical issues require some technical background to be grasped, and the resulting strategies can be complicated. Under these conditions it can be challenging to obtain management support.

The goal of this report is to provide a high-level assessment of the systems technologies that are currently available or are feasible in the near term. This assessment includes a description of capabilities as well as limitations inherent in the technologies. It also matches technical capabilities to current requirements. The report avoids a bake-off approach of comparing particular vendors. It is more strategic than tactical. The CAD/CAM/CIM requirements identified in 1997 are still valid, and they provided the groundwork for this report. Those requirements were mainly functional in nature; this report also attempts to identify the non-requirements, that is, the implementation constraints that systems technology must respect. Each section in the report begins with some background on a particular functional area and, then, describes the current state of the technology as it relates to that area. The focus of this report is an assessment of systems technology support for shipbuilding production processes. Therefore, the background section provides only a thumbnail overview of each production process area. The state of the art section addresses in detail the current state of the art for systems tech for that area. Moreover, each section ends with a discussion of the opportunities that may be applied in that area. Finally, the report concludes with a summary of these opportunities in the form of a road map for future development.

II. Systems Technology Areas of Investigation

1. Improved Definition of the Product Model to Capture Manufacturing Data

a.) Current CAD Capabilities

Background

This section describes the requirements and capabilities of computer-aided design (CAD) and Product Data Management (PDM) systems with respect to shipbuilding production processes. CAD and PDM systems are the key elements of the shipbuilding integrated development environment

(IDE). They support the creation and configuration management of the design and engineering work products for the ship. As such, the influence they have on production process is significant but indirect.

A shipyard's Integrated Development Environment is comprised of a combination of CAD, CAE and PDM application services. In the mid-1980's Litton Ingalls Shipbuilding (now Northrop Grumman Ship Systems) implemented Calma 3D System (now PTC's Dimension III). In the 1990's the first tier U.S. shipyards migrated to 3D CAD tools (at first homegrown and later customized COTS). This generation of CAD tools was driven by the requirement to minimize the creation and management of product model data. The goal was to capture the product design data once and re-use it many times. This entails a change from a 2D drawing oriented view to a 3D product model view. In most shipyards this migration was overseen by the engineering department and as part of the migration, the myriad of CAE tools were also interfaced with the new CAD platform. The goal of extensive re-use cannot be realized without effective configuration management – keeping track of which versions of the product model files were associated with which downstream application. This requirement was addressed by the introduction of PDM systems.

In the areas of CAD and PDM, however, the shipbuilding industry found itself in an unfortunate position. The information requirements for ships are much more challenging than the information requirements for automobiles or aircraft, yet the shipbuilding industry represented only a small portion of the market share for CAD and PDM vendors. A naval combatant (carrier or submarine) consists of 2 to 4 million piece parts; an automobile consists of about 15K parts; and an aircraft 250K parts. Moreover, for every dollar the shipbuilding industry spends on CAD/PDM, the aerospace industry spends ten dollars, and the automotive industry spends $20. The disparity is striking, and it is only natural that the CAD and PDM vendors would respond more enthusiastically to the customers with simpler requirements and more money. The end result is that CAD and PDM systems are developed, first and foremost, in response to the requirements of the automotive and aerospace industries. The shipbuilding requirements that are above and beyond the basic functionality are not addressed in the standard COTS offering. Those requirements are met either by customization done by the shipyard itself or by enhancements/accelerated development done by the CAD/PDM vendor but underwritten by the shipyard or its customer. A specific example is the Department of the Navy (DoN) has invested several million dollars in the development of Dassault Systemes' CAD product (CATIA) in support of the current destroyer acquisition program DD(X). The goal of the investment is to have needed shipbuilding functionality incorporated into the CAD platform. On top of the investment, the DoN and participating shipyards will then have to buy the software licenses to use the product they paid to have developed.

State of the art

Most people in ship design and engineering community understand the capabilities of CAD and solid modeling. They recognize the differences between producing engineering drawings and CAD models. However, even among shipbuilding designers and engineers, there is still a lot of confusion about the role of PDM systems. One reason for the confusion is the PDM systems on the market today were designed to support the processes of the automotive and aerospace industries. Users in the shipbuilding world have difficulty mapping the functionality of the PDM system to the requirements of their own design processes. Traditional PDM systems emerged from the need to manage product model data so that it could be created once and re-used many times. The way PDM systems address this challenge is that the master copy of the product model is stored in a secure datastore (sometimes referred to as a 'vault'), where its data integrity can be protected and where changes can be tracked and controlled. Users only deal with copies of the vaulted data. There is a notion of check-in and check-out as users reserve the right to edit or to view the data. Only one user at a time has the right to change the product data. Today's production PDM systems are built around the notion of documents, and the primary type of document is the CAD model file. Accordingly, these PDM systems manage data at the model level. The other major functions of the PDM system include the association of attributes to the CAD models, the management of other electronic documents (in the vault) and the association of documents to other documents. The PDM system provides configuration management of the documents, keeping track of versions and effective application to versions of documents. As part of its data management function, the PDM system provides the means to classify information. Documents of similar types can be grouped together in named classes. One important grouping is the engineering bill of material, which describes the as-design product structure of the models as they are organized as components and assemblies.

One of the major deficiencies of today's PDM systems, with respect to shipbuilding requirements, is that the PDM systems manage data at the model (or document) level. However, ship design and construction requires the management of data at the piece part instance level. Typically, a CAD model of piping or structural system contains hundreds of parts, but the traditional PDM system just manages the model itself. The PDM attributes apply to the model per se; there is no mechanism for managing attributes for each instance in the model. The same holds for the PDM functions. For ship design, it is the instances that must be organized in a product structure. Each instance must also be configuration managed, effectively assigned, and linked to its associated documents. This shortcoming is closely related to the design of the CAD system. The first-generation CAD systems were also model-based. The CAD model was the unit of functionality. In the early CAD systems the constituent items that made up a model were not even given permanent identifiers. These transient identifiers would change each time the model was opened. This improved the processing speed, but made it impossible to accomplish any data management of items within a model. By the same token, the first generation PDM systems adopted the philosophy that one model corresponds to one single part. This philosophy works for the design of mechanical products, but not for shipbuilding. The second generation integrated product development environment (IPDE) systems are currently in place at the first tier shipyards. The most important new characteristic of these systems is that they manage instances, as well as models. However, these systems had to be custom built for the shipbuilding industry – either by the shipyard itself or as a special development executed by the CAD vendor and funded by the shipyard.

For the last few years the nature of the CAD data itself has been a major concern for CAD vendors. Partly motivated by complaints from the shipbuilding industry, but also driven by the need to improve CAD capabilities for other industries, the CAD vendors have been exploring ways to manage CAD data at the piece part rather than the model level. The first avenue that was pursued was the notion of exploding the model. A model would represent a session from the user's perspective, but when the model is saved it would be exploded into its constituent pieces, and each piece would be stored independently in the CAD database. When the model was re-opened, the pieces would be re-assembled. Progress with this approach has been slow especially for models of the size found in shipbuilding. The issues involve access performance as well as the difficulty of managing the relationships. Independently, the information technology industry has been pursuing a similar problem from a different direction. The management of information within structured documents is an analogous problem. The document itself is the primary container for its constituent parts, yet there is usually a need to access the parts of the structured document by themselves. Using XML technology, the approach has been to "expose" the contained items. That is, it is possible to access individual component items even though the document is still managed as a whole. There are benefits to this approach; there is a cohesion to a CAD model or a to a document. More often than not, the model/document is accessed and used in its entirety. The ability to access individual elements is a secondary requirement and should not be enabled at the expense of this capability.

The second deficiency of the today's PDM systems is in the area of configuration management. Management of the configuration and effectiveness are expected capabilities of a PDM system. However, in today's systems these capabilities have been designed primarily in support of automotive industry requirements. Many PDM systems have extensive configuration management modules, which manage options and variants. In some systems configuration management of options and variants are even controlled by design rules. For shipbuilding applications, managing effectiveness takes the form of hull applicability. The capability to manage options and variants is non-value-added overhead. Moreover, as with shipbuilding CAD, shipbuilding PDM needs to manage instances. Typical PDM systems manage parts only. A part may have any number of occurrences within a product. An instance is a single occurrence of a part at a particular location in the product.

Finally, an important aspect of shipbuilding product data is the management of joints (or connectivity) between instances in the product. These may be structural as well as piping joints. Today's PDM systems do not emphasize this capability, and shipbuilders are left to custom develop the code to manage joint data. This capability should be part of the PDM system.

Opportunities

CAD/PDM system enhancements (e.g., instance management)

The opportunities in the CAD/PDM arena depend predominantly on the business cases of the technology vendors. The shipbuilding industry should however, make improvements to the definition of its requirements. As we have seen ship design and construction requirements are very complex and are often interwoven with confusing technical details. Today requirements are conveyed to the CAD vendors by individual shipyards or individual programs. There should be a great effort within the industry to define the core requirements that are needed to support the ship design and construction processes. These requirements must include remedies for the deficiencies described above: instance-management, shipbuilding-specific configuration management (hull applicability), and management of joints.

Feature-based design

The first generation of IPDE systems among U.S. shipbuilders was devoted largely to the migration from 2D drawings to 3D product models. The 3D models employed the new technologies for solid modeling. To a lesser extent, some of the discipline-specific CAD applications employed a feature-based approach. However, there is no comprehensive feature-based design capability in place among the first tier shipyards. The availability of feature-based design product model is a pre-requisite to the automation of many shipbuilding production processes. This issue is explored in more detail below.

CAD/PDM data sharing

Most of the work in the area of CAD/PDM data sharing originates with the STEP standard. The Standard for the Exchange of Product model data (STEP) is the international standard, ISO10303. It consists of a voluminous series of documents, which provide different industries with the capability to exchange and share the information that defines a product model. Such information sharing may be between shipbuilders or among systems within a shipyard. This product data is designed to support the entire product development, life cycle. Today the first set of shipbuilding specific application protocols are being completed and adopted. The first generation standards focus on an explicit geometric representation of the product. There is some attempt to capture design features in these models, but it is not comprehensive. As described in more detail below, the next generation information model needs to be able to capture shipbuilding specific design features that can be related to the appropriate manufacturing features.

b.) Shipbuilding product models, drawings and STEP-NC

Background

This section describes the state of the art of product modeling for the shipbuilding industry, particularly as it relates to production processes. One of the major software tools used today in the U.S. is Tribon where in Europe and Asia, a popular tool is Hicadec.

Most U.S. shipyards have recently completed a migration in product modeling capabilities from systems in which the engineering drawing was the primary work product to systems in which a digital 3D product model is the primary work product. This migration represents a significant investment and is built on the premise that the CAD product model can be re-used in many downstream applications. Because its market share is limited, the shipbuilding industry, for the most part, has accomplished the migration using CAD systems that were developed in response to the requirements of other industries. The first generation migration consisted of the capturing of explicit solid geometry representations. However, geometry by itself does not constitute a product model. For example, a purely geometric model can appear on the screen to be the model of a piping system without actually having the characteristics of a product model. The cost justification of creating a product model is that it will be re-used again and again by downstream users and applications as well as systems. Nevertheless, virtually all shipyards are still producing 2D drawings in addition to the CAD product model. In fact, in most cases the CAD system is used as the means for generating the engineering drawing. However, the engineering drawing is more than just a published view of the product model. Engineering drawings still capture information that is not captured anywhere in the product model.

State of the art

The rationale for the migration to 3D CAD systems was the ability to create a complete, product model that could be captured once and used many times. The adoption of solid modeling of nominal geometry is only the first step in the process of enabling this capability. The first generation CAD platforms adopted by the shipbuilding industry placed a heavy emphasis on tools to create and edit solid geometry. This was a natural evolution since solid modeling technology was just coming to maturity during that time, and CAD vendors were focusing most of their resources on that technical challenge. However, capturing the nominal solid geometry is only the first step in the definition of a re-usable product model. Raw geometry becomes re-usable after it has been associated with design features. A feature is a data entity, which represents specific meaning with respect to a product. It is a user-oriented aspect or characteristic within a product model. The definition of features is related to the object-oriented approach for information modeling. With more meaning captured, it becomes easier for later applications to re-use the product model. Features are closely related to parametric modeling. Features are instantiated by assigning actual values to one or more variable parameters. In addition, constraints are used to specify relationships between features and feature parameters. Together, features and constraints begin to define the design intent behind the product model. Moreover, with feature-based systems, better definition of the product model is available facilitating the use of Group Technology.

The first generation of feature-based design tools focused on geometric features. The earliest systems supported the ability to generate families of shapes from a 2D profile and designated parameters. This capability supported mainly mechanical design scenarios. In the shipbuilding industry, these parametric systems have been used in the conceptual design process, in which the ability to do what-if analyses is important.

The first major value-add of feature-based modeling is its ability to capture design intent. Design intent is missing in CAD systems that support only solid geometric modeling. Furthermore, even though some systems support feature-based modeling, that information is typically lost in the process of data exchange because feature-based exchange capabilities are not widely supported by CAD vendors. A feature-based representation augments the geometric model with a representation of design freedom, geometric constraints and design features. Design freedom indicates the range of allowable design alternatives. Geometric constraints make explicit the limitations imposed on the allowable design alternatives. Geometric constraints include such characteristics as parallelism, perpendicularity, symmetry, and tangency. Design features are high-level design constructs with parameterized dimensions. They support the definition of families of parts in which dimensions may depend on other (possibly non-geometric) parameters.

The development of international standards for sharing geometric features has lagged behind the implementation of feature-based CAD platforms. This is understandable since features are largely user-oriented constructs, which require a degree of customization. The richness of a set of features is a competitive advantage for a given feature-based CAD platform. Nevertheless, in the STEP community, ISO10303-108 is under development. It provides a standard mechanism for associating parameters with model dimensions (and with other variables). It also supports the representation of geometric constraints and describes how to associate them with geometric elements. Finally, it supports the ability to model complex shapes based on 2D profiles.

Another major value-add of feature-based modeling concerns the handoff of the product model from design to support production processes. After a design product model is complete, computer-aided manufacturing (CAM) and/or computer-aided process planning (CAPP) applications can be used to add manufacturing features. Manufacturing features need to be kept separate from design features. Manufacturing features provide the meaningful constructs that describe how to manufacture the product; they may change for different manufacturing facilities or for other reasons and, thus, should not be intermingled within the design product model. As with design features there is not yet a standard set of manufacturing features. A harmonized set of manufacturing features is required to support interoperability not only between CAM systems at different shipyards but also between CAD and CAM systems. The lack of interoperability between CAD and CAM systems is costly. Today, in many cases, the loading of the CAM system involves costly data conversions, misinterpretations of meaning and errors, which may result in lost time and costly rework.

The STEP-NC standard is under development; it will address the interoperability of CAD, CAM and CNC systems. In today's environment machines on the shop floor are populated with information that is conveyed in two steps. The first step is the construction of the CAM or CAPP model, which begins with nominal geometry from a CAD system. That geometry can be in a standard format such as IGES, APT or STEP. However, the exchange of design features is virtually unsupported. The final product specification is still conveyed by means of 2D engineering drawings. The product specification is the information, which, together with nominal geometry, describes how the product is to be produced. The second step entails the transfer of the CAM model to the CNC machines – at least for those production processes that can be automated. Today this data transfer is nearly always accomplished using the part-programming standard, ISO 6983, which is also known as the M&G code. This standard was developed about forty years ago. Even though it has the benefit that it actually works, the M&G interface often proves to be a bottleneck. M&G code is produced by means of a post-processor, usually implemented in the CAM system. While the CAM model consists essentially of geometric and manufacturing features, the M&G file contains only low-level instructions that guide the movement of the CNC machines. Of course, each machine has its own capabilities and specialties, and for full compatibility these extensions need to be incorporated in the CAM system. Newer machine tools have more capabilities and more opportunities for optimization; in fact, it may be possible to adjust the process plan based on feedback from the machine itself. However, data flow in this environment is only one way. Since the process plan is generated in the CAM system, it is impossible to take advantage of such potential optimizations.

The technical approach embodied in the STEP-NC standard is to develop an integrated data model (encompassing CAD, CAM, CAPP and CNC functionality). The integrated data model includes geometry (CAD), features (both design and manufacturing), and tool definitions (including both the geometric configuration of the tool as well as its technological information). The purpose of the integrated product model is to provide enough information to support the intelligent generation of the tool paths needed to manufacture the part given the available manufacturing tools. This includes not only the geometry of the tool path, but speeds and feeds as well. The work plan can then be optimized based on the individual machine and potentially based on feedback from the operating conditions of the machine itself. The STEP-NC product model begins with the nominal geometry (and design features) from the CAD product model and represented in STEP form. The CAM system, then, enhances this model by associating it with manufacturing features, such as pockets, borings and grooves. In addition, the technological data for each machine is represented through available operations and tool constraints. Finally, a working plan is captured, which is a description of each working step that must be performed. The working plan designates what needs to be done, not how it is to be done. The intelligent manufacturing model, then, consists of the combination of the working plan, nominal geometry, manufacturing features and tool descriptions. From this information, a CNC controller can employ its own algorithms to define the low-level operations that best execute the plan. The integrated model would be the same for all compliant controllers and represents a more complete and computer-interpretable product specification. As a fall back, the standard also supports the explicit representation of the tool path. Currently, the STEP-NC standards community is focusing on models for milling and turning.

The STEP-NC effort began with a definition of the user requirements for turning and milling as part of ISO 14649. This work has been harmonized with the STEP standard in ISO10303-238, the application protocol for STEP-NC. This standard defines the interface between CAM manufacturing features and CNC systems. It also provides information interoperability with the nominal geometry defined in the CAD model.

Although the technical approach of the STEP-NC work shows promise for the shipbuilding industry, the usefulness of the current activities is limited. Milling and turning processes play a minor role in the shipbuilding process. The most pressing areas for manufacturing in the shipbuilding industry are in the specialized areas of structures and piping. The STEP-NC approach is well suited to these areas, particularly as means for automating the manufacturing processes and the CAD to CAM/CNC interfaces. The requirements and state-of-the-art for structural and piping manufacturing processes are described in detail below.

There is, however, a more general problem facing the shipbuilding industry. Shipbuilding product processes are not limited to manufacturing processes; in fact, shipbuilding is largely an assembly and outfitting process. With today's technology there is still a need for better support, from the digital product model, for assembly and outfitting. In U.S. shipyards today, 2D CAD platforms continue to flourish, even though most of the shipyards have already adopted 3D CAD platforms and make extensive use of 3D product models. Even though they have increased utility, 3D product models are expensive to build. They are more expensive than simply using computer-aided drafting tools. The current situation is that the 3D CAD model is used as the means to help generate the 2D engineering drawing. The 2D engineering drawing is still the primary means of disclosing the product model and product specification. Often the drawings are printed and distributed in paper form, but demand for this information is so great that, in some cases, the drawing itself is distributed in digital form as a raster image. The raster image is a dumb reproduction of the drawing; it carries no computer-interpretable information. Nevertheless, the engineering drawing is the primary tool used both for construction and post-delivery support.

The biggest problem with the engineering drawing is its strength as a means of communicating the complete product specification. The drawing is easily understood by human users and is the only place in which the complete product specification can be found. The engineering drawing is able to convey the product specification information for assembly and outfitting that is missing from the product model. In today's systems the 3D CAD product model, which consists largely of nominal geometry, does not contain all the information needed to realize the product. These requirements include the nominal geometry of the product, the 3D product model (discipline-specific) and the product specification. The product specification information includes such things as critical dimensions and tolerances. The product model provides an infinite number of dimensions; however, only a small number of dimensions are critical for manufacture and assembly. Today's 3D product models do not have the means to designate which dimensions are critical. Similarly, tolerances need to be associated with the critical dimensions, and today this is done only in the engineering drawing.

Problems arise when the 3D product model is used as the means to generate the 2D engineering drawing. Essentially, the product model and the drawing are two different views of the same design in two different formats. The engineering drawing is a complete product specification, but it is not computer-interpretable. Even though its information can be readily understood by human users, it cannot be re-used by downstream applications. Each view of the design must be maintained separately, and the danger exists that they could get out of synch. The shipbuilding product is characterized by a very large quantity of piece parts, which change substantially over a long period of time. The configuration management requirements are more than doubled by such a dual representation. The result is a significant non-value-added step in the ship design process. The engineering drawing needs to be checked for consistency and accuracy. Even in shipyards that make extensive use of the 3D product model, most checking is still done with respect to the drawing. In addition, the drawing itself needs to be developed and published. The drawing consists in part of information generated from the CAD product model (selected views) and in part of information that is transcribed and captured only in the drawing. Without one single computer-interpretable representation of the product model and product specification, advanced automation of the related shipbuilding production processes cannot be realized.

Opportunities

Digital product specification

One of the foremost opportunities for improved production processes is the ability to create a complete product model and product specification, in computer-interpretable form, in one system (possibly modular or distributed). There are several pre-requisites to such a capability. First, there is the need for a standard, feature-based representation for each of the design disciplines used in shipbuilding. Work on such a standard is well under way with the STEP shipbuilding application protocols (AP).

These standards will cover ship structures, piping, HVAC and arrangements. User's guides have been developed to use AP212, Electrotechnical Design and Installation. AP226 Ship Mechanical Systems is currently under review. New AP development areas that should be addressed include outfit and furnishings, electronics and mission systems. The second pre-requisite is support for the standard product data model among CAD system vendors. This entails not merely the translators for the exchange of the product model but also the functional capabilities to create and edit the shipbuilding-specific product models. The next pre-requisite, then, is the ability to model tolerances, critical dimensions and the rest of the product specification information needed to manufacture, assemble and construct the product. The next pre-requisite is the definition of the manufacturing features (and other STEP-NC constructs) needed to interface with automated manufacturing tools. These features must cover all the shipbuilding trades. The final prerequisite is the system technology for accumulating and publishing an integrated product model and product specification. In order to be successful, this technology must be perceived as a satisfactory replacement for the engineering drawing among all users of drawings, and it must present a computer-interpretable product model/specification that can be re-used by other applications.

2. Fabrication

a.) Steel

Background

This section describes the systems technologies that support the lofting and nesting processes for steel processing. These processes depend upon design product model data; however, the lofting and nesting processes are actually CAM processes. These processes begin at the release-for-production of the design product model and end with an individual cut part, prior to its use in an assembly or its installation on the ship. The NSRP Benchmarking Report NSRP[2001] found that for world-class overseas shipyards lofting and nesting are for the most part integrated with engineering processes – having replaced manual lofting and template making. In the U.S. all yards now use computer-aided lofting and nesting systems that are derived from a CAD model. The report adds that, "Many of the procedures would be world-class if there were direct links to NC cutting and forming machinery and if a structured method of determining shrinkage allowances was in place using data that had been produced from statistical process control." In other words there is room for much more automation than is found today.

Lofting and nesting support the manufacture of individual plate parts. A structural part is a piece part that is fabricated from raw stock, mainly by cutting. It may be in the form of plate (flat or formed); corrugated material; or profile. A corrugated structural part is made from corrugated stock material. A profile structural part is made from material that is extruded based on a two-dimensional cross-section. The manufacture of profile parts is supported today primarily by means of drawings and sketches. Plate is made from flat shaped stock material, which is nominally planar in shape. A formed plate part is modified by a bending operation after it has been cut. Up until the time that plate is formed, it participates in the lofting and nesting process just as a flat plate would. The overall lofting and nesting process is illustrated in Figure 1:

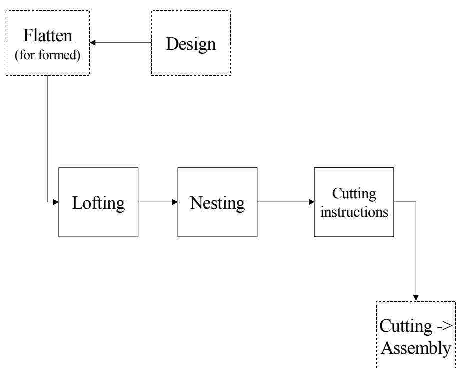

Figure 1: Lofting and Nesting

Lofting

For shipbuilding applications lofting is the process of defining a single piece to be cut from flat stock material. Lofting is in many respects a flat pattern process, most of which can be solved using two-dimensional representations and rules. In terms of the computerized machine control systems, however, the end result is a 2-½ D process. The cutter can move in the x and y directions and also in z, but not at the same time. Moreover, the complete definition of the lofted piece may include bevels on the edges, which introduce a 3D component to the process.

Structural parts, such as plate parts, are designed in context in 3D CAD systems. Individual parts are managed as components within a larger construct. There are typically many parts in a structural product model. Moreover, the CAD model locates each structural part in relationship to its end use. The CAD model describes not only how it is related to other structural parts within an assembly, but also how it is located and oriented with respect to its final installation. A great deal of this information is superfluous when the objective is to manufacture the plate part. In the CAD model the part is represented as a solid; in the lofting process, a two-dimensional outline (with some parameters) is sufficient. In the CAD model, the part is located in 3D space; in the lofting process, the part needs only to be located in a two-dimensional manufacturing space. When the source of the design data is a paper drawing, the lofting process adds information. When the source of the design data is a CAD model, the lofting process also requires the elimination of information. If the source of the product data is a 3D CAD model, then the first step of the lofting process consists of the extraction of one part's worth of data, one at a time, for each part in the model. At this time, the defined transformation takes the part from its CAD coordinate system, to a specified location in the manufacturing coordinate system. The solid model must also be converted to a two-dimensional outline with attributes such as thickness.

The next step of the lofting process is the addition of manufacturing features. The design model captures a nominal final condition of the plate. The design model should be kept separate from the manufacturing features because the same part could be manufactured differently depending on shipyard, end use or other manufacturing specific requirements. In fact, for steel plates in shipbuilding applications, the relationship of the design model to the lofted (manufacturing) model is quite different from that found in other disciplines and other industries. For example, for parts that are produced by milling, the design model typically describes the final manufactured shape of the part. Manufacturing features define the operations that must be applied to a stock part in order to produce that shape. Operations always consist of the removal of material. The situation is different for lofted plates; the design product model only partially represents the shape of the finished product. The design model typically describes square edges that abut to other parts. However, these edges are sometimes beveled during manufacture and then filled with weld during assembly or installation. As a result, the manufacturing product model may have to alter the shape of the edge of the plate. The lofted model represents an in-process version of the shape of the plate. This means that the CAM system must be capable of editing the shape of the design product model; it needs a fairly complete CAD capability.

Additional manufacturing features also alter the original design model. For example, some plates require added stock for fit-up. The lofted model must be able to represent the geometry of the new shape. On the other hand, some plates need to adjust to compensate for weld shrinkage. Part of the lofting process entails the capturing of these changes to design model. In addition, manufacturing features need to be added to define the welding requirements for each edge. This may include the selection of appropriate weld type as well as the correct bevel. These decisions may be based on manufacturing requirements that vary from shipyard to shipyard or even for different end uses of the same part design.

The final step of the lofting process is the transfer of the lofted model to the cutting NC controller. In some cases the lofted model may be transformed directly to NC code, but the more common case is that the lofted model is imported into a nesting system. Today that means that the data is conveyed using some surfaced-based file format. Surfaces are needed to convey information about bevels. The most common formats are IGES, DXF and APT. However, all these formats are somewhat out of date, and none completely represents the information that needs to be conveyed for full automation). These formats are predominantly geometry based, driven by the capabilities of CAD systems. What is needed is feature-based representation that is more concise and that conveys a more intelligent representation that can be used as input to the nesting system.

State of the art

There are three different strategies that have been used to provide lofting systems technologies support in U.S. shipbuilding. Some CAD vendors, particularly those that offer shipbuilding specific packages, provide lofting capabilities as modules of their CAD offerings. A variant of this approach entails the integration of lofting and nesting capabilities in the same CAD package. The third approach, followed by a number of shipyards, is to build custom applications that link their CAD systems and their steel processing systems. These applications also include lofting capabilities.

Integrated CAD-Lofting-Nesting

KCS offers the TRIBON M1 Hull package, which integrates CAD, lofting and nesting capabilities. The TRIBON system is tightly integrated and uses an approach that is feature-based. The basic feature supported by TRIBON M1 Hull is the panel. A panel is a functional structure, and it is used to represent structural items ranging in size from angle brackets to decks and bulkheads to webs and girders. The panel is the data structure that captures the associations between the various structural parts that comprise it. These associations are a pre-requisite for automating the selection of manufacturing features during the lofting process. It is not enough to know the characteristics of a structural part in order to loft it; it is also necessary to know the characteristics of its connected parts. In this context, TRIBON also provides a capability for rules. In many instances actual geometry at structural joints can be computed based on the conditions described by the panel and the base of customizable shipbuilding rules and standards.

Within its CAD modules TRIBON supports the definition of formed parts, and flat plate parts. Curved parts are developed interactively, often based on surfaces defined by other panels. A curved panel capability can be used to build complete shell panels, including shell plates and detailed descriptions of longitudinals and/or transversals. The Planar hull module is used to model panels that represent flat plates, including plates, stiffeners, brackets, and flanges. TRIBON manages the structural joints such that parts are connected to edges of adjacent parts, allowing a portion of the lofting process (generation of edge geometries) to be automated. Finally, because all this work takes place within the CAD environment itself, other geometric capabilities for lofting are well supported. For example, a facility is available to compensate for weld shrinkage.

TRIBON also includes its own nesting sub-system, which is driven directly from the TRIBON lofted model. This system is described below.

Integrated CAD-Lofting

Intergraph's I/LOFT module also integrates lofting and CAD capabilities directly. However, the Intergraph solution does not include its own nesting capability. As with TRIBON, the Intergraph package supports the extraction of individual parts from the CAD model for lofting. This is an interactive process in Intergraph and is integrated with a production planning/assembly capability, in which individual structural parts can be grouped into assemblies, which feed larger assemblies as well as blocks or units. The assembly capability also provides a capability by which lofted parts can be compared to determine which parts are identical. The I/LOFT package also provides an "unwrap" function for formed parts. The unwrapped plate model contains the characteristic lines, including structural markings indicating material direction;

roll lines for curved, shell plates; datum lines for accuracy control; and waterlines.

The I/LOFT module also supports the addition of manufacturing geometry. Bevels, extra stock and compensation for shrinkage can be modeled geometrically in the CAD model. In the Intergraph system the adjusted model feeds the lofting, nesting and manufacturing processes.

Custom Lofting capabilities

The highly integrated single-system approaches are, in general, not used in the bigger shipyards. Single-system approaches sometimes lack some functionality that is required for naval shipbuilding. For example, submarine and carrier programs rely heavily on hull effectiveness for the configuration management of design to manufacturing data. Moreover, these shipyards tend to favor best-of-breed applications among the sub-systems that support the overall design-lofting-nesting-cutting process. One factor in the deployment of first-generation systems is that the shipyards differ with respect to manufacturing capabilities and constraints and consider some of these differences as key discriminators. Accordingly, the manufacturing systems at such shipyards were best served by custom-built applications. For example, Avondale shipyard uses the SPADES system for steel processing. The current version imports information from Intergraph ISDP. Electric Boat uses custom-built software that accesses product design data from CATIA. In both systems the information that captures the relevant design and manufacturing features is often managed outside the CAD model itself.

Opportunities

This section describes some areas in which new systems technologies capabilities could improve the efficiency of the lofting and nesting processes:

Feature-based design product models

Today's CAD systems are predominantly geometry-based and do not adequately capture design or manufacturing features. The result is that it is very easy for operators (even experienced ones) to build geometric models that look complete but which fail to capture information required for CAM processes such as lofting. Features are a more concise and more meaningful means for representing the product model. Geometry can be readily generated from features, but features cannot be readily generated from geometry. Current shipbuilding IPDEs make heavy use of geometry-oriented CAD models. Major cultural and technological changes need to be made before a feature-based is widely deployed across the U.S. shipbuilding industry. This is especially evident in the processes connected with steel processing. It is often difficult (or impracticable) to derive design intent from geometry alone. In fact, even when CAD geometry can be imported into the CAM system, it cannot be used until a large volume of irrelevant geometric detail is filtered out from the model. Since there is nothing in the CAD to indicate the purpose or intent of most of the geometry, the process of filtering cannot be automated and is usually prohibitive for an operator. As noted above, the custom CAM systems deployed at some shipyards manage the necessary design and manufacturing features outside the CAD environment per se. These services need to be made available in conjunction with CAD system but in a way that is decoupled from the CAD geometry. CAD tools need to provide the ability for the design to designate which information is pertinent to downstream applications such as CAM.

Product data management for CAM (lofting) data

Today's shipyard IPDEs have all adopted some degree of Product Data Management (PDM) capability; the kind and degree varies widely from shipyard to shipyard. However, there is an opportunity for improved configuration management and increased productivity by more effective management of shipbuilding CAM information. It is a very costly mistake if steel is cut to an obsolete product model. CAM product models should be managed independent of their supporting CAD models. The introduction of CAM information directly into the CAD model makes the design model very resistant to change and inhibits design improvements and technological innovations. Improved facilities for the association of CAM product data and CAD product data are needed. It should be possible to associate CAM work products to each other as well as to relevant CAD model at the piece part level. For example, if the design of piece part is changed, the system should be able to ensure that no nest file that contains the part will be cut. By the same token, it should be possible to perform a check on a nest file that the design for each piece part in the file is still valid. The problem is especially important to yards that rely on hull effectiveness to manage design work products.

Automation of the lofting process

As stated in the NSRP Benchmarking Report (NSRP[2001]) the automation of the lofting process is a key area for potential process improvements. In most U.S. shipyards the lofting process has been computerized and has links to the CAD product models, and, in fact, some degree of automation exists. However, there are still many manual steps involved. For example, an operator typically determines and enters the manufacturing features that consist of bevel selection, weld shrinkage adjustments, added stock, etc. These steps could be further automated, but there are some pre-requisites to this level of automation. These decisions are based on manufacturing capabilities and associated rules that vary from shipyard to shipyard. There needs to be a way to represent and manage these manufacturing requirements and rules. This includes the rules for associating welding types with manufacturing requirements. The system that supports these rules must be flexible enough so that the rules can be tailored per shipyard.

Improved interface to accuracy control systems

The enhanced PDM system described above is a pre-requisite for improved interfaces to accuracy control systems. The PDM system should be designed to manage the association of lofted and nested items with their respective inspection requirements and inspection results. In addition the PDM capabilities lofting (and nesting) systems need to begin utilizing a feature-based representation that is suitable for generating inspection features. Better tools are needed to transform manufacturing features, specific to the constraints of the lofting process and to geometric representations.

Need to move away from obsolete data formats

The lofting and nesting processes, especially for loosely coupled systems, are very dependent on the sharing of complex CAM product data. Unfortunately most of the exchanges are still done using obsolete formats such as IGES or APT. These formats are limiting because on the one hand, they are geometry oriented, and, on the other hand, are based on technologies that are no longer widely supported. A feature-based neutral format needs to be developed and widely implemented among lofting software systems. This format should be standards-based using the STEP and STEP-NC framework. The data format should be based on XML so that these systems can take advantage of the wide range of software tools now available for managing XML data.

Better support for inter-company data sharing

Today it is difficult (if not impossible) to use CAD-based design data from one shipyard to drive the lofting and nesting processes at another shipyard. The typical scenario is that an opportunity for work sharing arises but there is not sufficient time to build a customized solution for such data sharing. The result is that the opportunity for work sharing is lost, or the data is re-entered manually. This situation applies not only between independent shipyards but also between sister shipyards within one corporation. Modern, neutral form data sharing capabilities will improve this situation. The NSRP Integrated Steel Processing Environment (ISPE) is addressing many aspects of this issue. A complete solution needs to support the ability to import or export at each step of the process starting with the nominal design model but also including the CAM features as well as the post-processed NC code. Different entry points support different alternatives and capabilities. For instance, with the CAD and design features, a shipyard can build its own manufacturing plan; this would be impossible if only NC files were exchanged.

Improved interoperability with ERP data

Lofting and nesting operations are typically controlled and scheduled within the shipyards ERP/MRP system. The sharing of structural processing work between shipyards requires more than just the design and manufacturing models; it is also needs to be incorporated into the shipyards management and control systems. This kind of work cannot be shared with a coordinated schedule. What is needed are better ways to share management and control data, and facilities to link the lofting and nesting operations with this shared information.

Decoupling of CAD and CAM data

Projects such as the NSRP ISPE project have recognized the need to de-couple CAD and CAM data. There is pressure from the specialized CAD platform to merge this data within a particular CAD environment. However, when CAM data is too tightly intermingled with CAD data it becomes very difficult to re-use the design data. For example, it is very difficult to accomplish re-design work on such data, and it is very difficult to share such data with other shipyards. The decoupling of CAD and CAM data is also a pre-requisite to the modularization of the steps in the lofting/nesting process. Best of breed tools for each step can only be deployed if there is a clear layering of the information required for each module.

Nesting

The nesting process consists of the arranging of flat parts or profile parts with respect to raw stock in order to maximize some user objective. Often, the objective is to minimize waste, but it could be some other objective as well. The nesting process is illustrated in Figure 2:

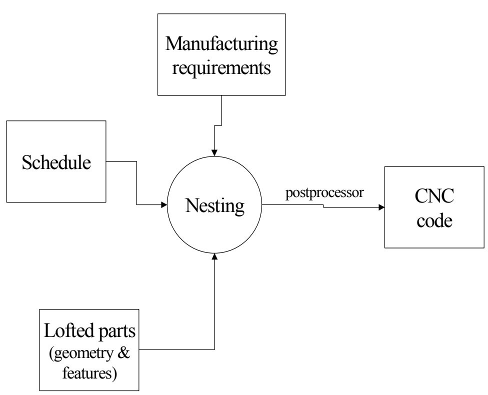

Figure 2: Nesting Process

The nesting process has three inputs: the manufacturing requirements, which include the definition of the objective of the nesting; the schedule, which defines the needs dates for a set of parts; the geometry and manufacturing features for a set of lofted parts. The nesting process arranges the lofted parts with respect to the raw stock. The output of the process is the CNC code, which will drive the cutting machines to produce the parts. As described above, there are two prominent systems approaches to nesting: nesting software provided by and directly bound to a CAD/CAM system (e.g. TRIBON and Foran) and nesting software that is decoupled from the CAD/CAM system (e.g. Sigmatek and OptiShip). The integrated approach has the advantage of close integration but it limits interoperability with other systems. The decoupled approach assumes that the lofting process has been completed. It typically accepts geometry in the form of IGES, DFX or APT file. For the most part feature information is lost in the data transfer process. This limits the potential for the application of rules in the nesting algorithms.

State of the art

Besides the strategic placement of individual pieces, the main task of the nesting process is the generation of tool paths from the CAD/CAM product model. Because the problem is quite constrained, it has been possible to fully automate nearly all aspects of the process, assuming that all manufacturing requirements are available to the system. The generation of tool paths entails adjustments for kerf (offsetting the tool path to compensate for material lost during cutting), for material expansion and for weld shrinkage. The tool path generation must also guarantee that no idle pass crosses over a previously cut part. Nesting software should also support the generation of marking paths as well as cutting paths.

One technical issue is the relationship between nesting software and the machine controllers for cutting. Today the interface between the nesting software is still based on M&G or ESSI formats. This is a machine-level interface and as such there are always minor differences between controllers. The nested model is always post-processed into a format suitable for a particular machine. This means that optimizations of tool path generation cannot be done at the controller itself, but must be completed beforehand and in a general fashion. Nevertheless, this approach has been widely adopted within the shipbuilding industry. A very small set of nesting software vendors is able to support a wide array of cutting equipment. In addition, the nesting process is somewhat different from other tool path generation processes because, on the one hand, it entails the organization of multiple piece parts resulting in added complexity; but, on the other hand, the limited feature set and geometric constraints make it a simpler problem. The upshot is that the current positioning of nesting software systems between the lofting phase and the cutting machine should not be changed.

Integrated Lofting/Nesting systems

Integrated lofting/nesting systems are typically used by smaller yards. These systems are generally functionally adequate, but they may not scale up to support the needs of defense shipbuilding. On the other hand, the smaller, integrated systems are richer in their use of feature-based design. This offers a better opportunity for optimizations in the nesting process.

KCS's TRIBON M1 Hull is one instance of an integrated lofting/nesting system. It is based on the feature-based product model that is created in the TRIBON Hull design and lofting system. The product model includes assembly and weld information; rules-based generation of manufacturing features; and definitions of structural joints. More product details may be found at the Tribon web site http://www.tribon.com.

Sener's Foran system also provides integrated lofting/nesting, which supports the nesting of both plates and profiles. Tool path generation is semi-automated. Parts for nesting are selected from the database those parts that match the thickness and material of the chosen raw stock. The nesting is accomplished by an operator's using a combination of rotation, translation and mirroring commands. The operator also has the ability to group parts and to duplicate parts or groups. The final tool path can be generated by defining the piercing points and the kerf position to be used for all parts. It may also be generated sequentially or contour by contour. More product details may be found at www.foransystem.com.

Decoupled Nesting Systems

U.S. defense shipyards use decoupled nesting systems. These systems are provided by vendors that specialize in the nesting process. The input to these programs is a neutral file representation of the geometry of each lofted part – usually in IGES, DFX or APT format. The major decoupled nesting systems in use at U.S. shipyards are Optimation's

Optiship and Sigmatek's SigmaNest. More product details may be found at http://www.optimation.co.nz/ and http://www.sigmanest.com/.

Opportunities

Improved integration with ERP

The nesting process is interdependent with the shipyard resource planning processes, including manufacturing schedules and material ordering. Current systems offer some degree of integration with ERP capabilities, but there is a need for improved interoperability between these systems. A standard representation of scheduling and other resource planning information would make it easier to integrate the nesting systems with the shipyard schedules. Nesting is typically performed nowadays as a batch process well in advance of need dates. A better integration with ERP systems would be an enabler for just-in-time nesting capabilities.

Accuracy control

Nesting systems do not typically maintain the identity of parts in the post-processed machine code. Nesting systems should support the addition of more meaningful information onto the cut plates themselves in order to expedite and improve the process of collecting meaningful accuracy control information

b.) Pipe

Background

This section describes CAD/CAM/CIM systems for the production of piping systems, with an emphasis on CAM/CIM. CIM for piping systems has a number of similarities with CIM for ship structures. If structural, manufacturing process can be thought of as a 2-½ D problem, then the manufacturing process for piping can be thought of as a 1-½ D problem. The piping system is almost completely specified by the composite curve that represents the piping path. The remainder of the product model can be specified by means of a relatively small number of feature-based attributes. As with structural CAD, however, the solid modeling orientation of the today's CAD platforms demands a full solid representation of the piping system. In some cases the solid model is in addition to the piping product model, but in some systems the solid model is presented instead of the piping product model. Those systems capture a solid model that looks like a piping system, especially in the context in which the piping system resides, but they do not represent a true piping product model.

The shipbuilding industry has focused most efforts in the area of CAD support for piping systems. Even the major CAD vendors now support product modeling of piping systems. The piping product model is fairly well understood and, in fact, well supported in other industries as well. The STEP standard for piping systems originated in the process plant industry and was later adopted (and enhanced) by the shipbuilding industry. In fact, a standards-based piping product model has been used for the basis of production data exchange in major submarine programs, and the exchanges have encompassed both custom developed piping CAD packages as well as COTS CAD platforms. Consequently, the piping discipline is ahead of some of the others in its use of a feature-based design model as the input to manufacturing and planning systems.

Manufacturing information for piping systems, as with structures, includes both CAM and NC aspects. The goal is to develop the machine instructions to automate the manufacturing process. There are two operations that need to be supported: nesting and bending. Nesting consists of determining the appropriate lengths to be cut and, possibly, marked. The bending operation requires that instructions be generated to drive a pipe-bending machine. Today these operations can be nearly fully automated based on the piping product model.

What is missing from the product model is the CAM information. Most important is the definition of the parameters of the actual machines that will be used for the cutting and bending. Each machine has its own constraints and limitations. For example, in the pipe bending process, if the pipe is too long or bent in a bad configuration, the pipe may collide with the floor, ceiling or with the machine itself. The necessary CAM data then includes not only a model of the machines themselves but also an indication of which machine will be used for each pipe detail.

Other parameters to be considered include springback, weld shrinkage and wall thinning. Because the product model doesn't always consider the CAM information, a manufacturing model is often created where the parts are modified to account for these added parameters. The part is modified in the manufacturing model where: it might be expanded to account for springback, it might be cut larger to account for weld shrinkage or maybe a different machine is chosen to avoid unwanted wall thinning. With this type of information, it is possible to construct a manufacturing plan with reasonable assurance of its productivity.

State of the art

Today CAM information for piping systems is captured and managed in custom applications at U.S. shipyards. Defense yards already manage, more or less, the same of amount of information within the piping CAD product model, and, in fact, Navy programs have successfully exchanged such models in support of co-production scenarios. U.S. shipyards have also developed the capability (in these custom applications) to perform design and manufacturing rules checking. After the CAM data is captured and associated with the CAD product model, it is possible to check for hits or other inconsistencies in the manufacturing plan.

Opportunities

Standard CAD/CAM exchange format

The standard for the exchange of piping CAD data is very well defined and beginning to be implemented; however, there is still a need to standardize the CAM information, including tool definitions, for piping. Currently, piping exchanges in co-production scenario may be shipyard specific. The necessary manufacturing features for piping systems should be standardized within the STEP-NC standards. There is a Navy Phase I SBIR that is currently addressing this issue.

CAD and CAM rules checking

Today CAD and CAM rules are checked for the most part within custom-built applications at each shipyard. Once the standard features for both CAD and CAM for piping have been agreed to, it becomes possible to have more open tools that perform rules checking. The first step is to move the rules out of procedural programs; current applications are still largely FORTRAN-based. A declarative rules engine will make it easier for shipyards to deploy an off-the-shelf CAD/CAM validator, which can be populated with its own rules.

Automated planning

A time-consuming step in the CAD/CAM process for piping is the definition of pipe details. A pipe detail represents a unit of manufacture. It is a unit that consists of one bent pipe (possibly with fittings at one or both ends) or a combination of straight pipes and fittings that when assembled lie in one plane. There are many ways to divide a piping system into pipe details (and later into assemblies), some more costly than others. There is a need for a system that can automate this planning process. The system would have to take into account the piping product model, the manufacturing constraints and requirements, the associated CAM data, and the costs associated with each manufacturing option. A current SBIR project is prototyping such a system.

PDM capabilities for configuration management

There is a pressing need for configuration management capabilities in the piping manufacturing process. A piping system is typically decomposed into assemblies, pipe details, and components. Each lower level entity must be configuration-managed with respect to its higher level collectors. Entities may be versioned at each level. Currently configuration management is performed either within the shipyard's custom-built application or in an ad-hoc manner. PDM capabilities are expanding to begin to manage data at a piece part level; these capabilities should be expanded so that they can be used to manage piping manufacturing configurations. The problem is the large number of items that comprise shipboard piping systems. The configuration management system must be easy enough to use so that users are not tempted to short cut the system.

Interference checking

There is a need for specialized interference checking for piping manufacturing. The pipe bending process is sensitive to hits as the pipe is processed. Conventional CAD systems are able to perform static interference checking on solid geometric models. The piping problem is different from this. On the one hand it is a dynamic problem since hits occurs at the pipe moves about the machine. On the other hand, it is a simpler problem from a computational geometry perspective. The interference problem can be solved as an intersection of curves (the pipe path) and surfaces (adjoining ceiling, walls, machine, etc.)

c.) Sheet Metal

Background

This section describes CAD/CAM/CIM systems for the production of sheet metal work products, with an emphasis on

CAM/CIM. CIM for sheet metal has a number of similarities with CIM for flat plate processing. Like the flat plate structural manufacturing process, manufacturing sheet metal can be thought of as a 2½ D problem. In some ways the sheet metal task is simpler. There are no bevel configurations to contend with, so in this respect the features associated with the edges of the sheet metal of simpler. There are fewer CAM requirements. On the other hand, because the material is cheaper and more manageable, the lofting process becomes more involved. While it makes sense to cut and manage steel plate one piece at time, typically an entire sheet metal assembly is cut and managed as a unit. Finally, the automation of the sheet metal manufacturing process can also includes a bending operation, which can potentially be generated from the CAM model.

The sheet metal process begins with a CAD model of the finished assembly. The first step of the CAM process is lofting. As with plate processing, the lofting stage consists of the separation of the assembly into each individual part, which can be cut from flat stock. Generally, there is more involved in this step than in the corresponding step for structures. The typical structural CAD model keeps track of the individual component pieces. This is not the case with sheet metal models. There are a number of ways that a flat sheet can be cut and bent to form a box; some of these ways are preferable to others given the constraints of the sheet metal shop. At the lofting step, the productivity of the assembly must be addressed. (As the design/build process is more completely utilized, these decisions may be pushed back to the design stage; however, when multiple shops are to be used, it is preferable to keep the CAD and CAM features separate from each other.) The lofting step may include an unrolling step for pieces with curved surfaces. The next step is nesting, which is a straightforward flat pattern operation. After nesting, NC code may be generated to drive the cutting and bending machines.

State of the art

In general, shipbuilding CAD/CAM requirements are more demanding than the requirements of other industries, and this situation is especially severe for sheet metal. The requirements for sheet metal CAD/CAM processing are complex and yet the potential payback for sheet metal is not perceived to be as significant as for steel or piping. Consequently, there is a lack of an integrated sheet metal CAD/CAM capability in commercial tools. Most of the integration work is currently accomplished by means of custom developed solutions at the shipyards.

The CAD requirements for sheet metal embody some constraints which, on the one hand, would simplify the deployment, but which, on the other hand, do not fit nicely in the mold of 3D solid modeling. Within the shipbuilding industry, there are two families of sheet metal products: non-standard, custom-design shapes and standard shapes that are re-used frequently (e.g., the shapes that comprise ducting systems). The design of non-standard shapes is done using conventional CAD tools and may be represented as surface or solid geometry. Because these shapes are made from flat sheets, all the geometry must be confined to developable surfaces. Solid geometry engines do not typically recognize such a constraint. Some surface modelers support the design of developable surfaces, but surface modeling is not in widespread use at shipyards.

There is a better opportunity for a feature-based, parametric approach with the standard shapes. Several years ago a number of shipyards agreed to a set of standard ventilation shapes that could be described parametrically. Early systems used custom-built code to create feature-based ventilation system models within conventional CAD platforms. Since then the standard shapes have been implemented in Dassault's CATIA system. This approach has the advantage of a concise representation from which explicit geometry can be readily generated.

Opportunities

Standard CAD/CAM exchange format

The standard for the exchange of ventilation CAD data is being standardized as part of ISO10303-227 version 2. This standard is incorporating requirements from the shipbuilding industry. The approach in this standard is based on a non-parametric definition of the associated geometry. There is currently no activity in the STEP-NC arena to define features for ventilation systems. The parametric features for ventilation shapes should be standardized. There is a need for better CAD support of the ventilation shapes and a better integration of these shapes with CAM systems. The CAD platforms provide the geometry engines that are needed to "unroll" developable surfaces.

d.) Robotic Welding

Background

Robotic welding is the process of using an industrial robot to control the motion of an arc, gas nozzle, laser, or other welding tip, and any associated wire feed or sensor equipment during welding. The welding path to be followed by the robot can either be taught manually by an operator, programmed off-line using specialized software, or automatically determined by a combination of software tools, geometry models, and sensor input. The process of mechanized or semi-automated welding, such as track systems, is included here as a specialized form of robotic welding. The use of robotics is typically associated with high-rate production and repetitive processes. These are not representative descriptions of the shipbuilding process, and robotics in general has a small presence in the shipbuilding industry. Robotic welding is widely used in the automotive industry, in high-volume repetitive operations, although this application is typically spot welding rather than continuous bead. Implementations of robotic welding in the shipbuilding industry have demonstrated significant reduction in man-hours and improved weld quality.

The motion of welding robots used in the shipbuilding industry is controlled by a variety of standard methods including operator teach pendants, off-line programming (OLP), physical alignment of guide tracks, and automated seam tracking. Manual teach pendants are used by an operator to train the robot on the actual work piece. These can also be used to initially align and calibrate the robot to the work when automated motion programming methods are used. With track based systems the motion of the welding apparatus is controlled by one or more physical guide rails. These guides are attached to the work pieces and used to align the welder with the joint. The welder then propels itself along the guide tracks through the use of servomotors. The fine motion of welding robots required to follow a joint closely or to incorporate multiple passes or bead patterns can be controlled by automated tracking systems. These tracking systems can be based on physical contact with touch probes or computer vision through the use of optical cameras or laser sights.

The control of robotic welding equipment often requires the use of specialized software. Robot motion can be programmed through the use of off-line programming (OLP) applications. OLP tools provide a virtual representation of the work piece and the robot, often making use of 3D computer graphics, and allow the operator to plan out and simulate different motion paths without moving the actual robot. The benefits of OLP are that motion planning can be done while the robot is busy doing production work, many different path scenarios can be tried without consuming any steel, and during the planning phase there is no danger of collision for either the robot or the operator.

Another software tool that is helpful in robotic welding is the use of welding templates or macros. Welding templates contain information about a particular weld type, for instance how to maneuver around a certain kind of geometry, settings to be used for joining two material types, or voltage/current parameters for a given joint type. Templates can be used to capture shipyard specific welding rules, or to enforce certain welding procedures where eventual certification of the weld is necessary. Templates and macros are created once and then reused many times, either as-is or with slight modification. By combining a group of templates together, weld planning can be accomplished quickly with a high degree of confidence.

State of the Art

Some form of robotic welding has been incorporated as a part of the standard manufacturing process at most major U.S. shipbuilders. Robotic welding is still a niche application, and is not used in the majority of ship joining activities. The majority of automated welding in shipbuilding is actually done with track systems rather than multi-axis robots. The most typical application of automated welding is in the panel line. This represents the most repetitive, high-volume activity in the overall shipbuilding process. The long, often straight, unobstructed seams in plate butt joints and stiffener fillets are an obvious target for automation. Another application area for automated welding is in hull erection and joining of major sections. Here again, track systems are used to make long weld passes in accessible areas. A number of shipyards are beginning to test the use of multi-axis robots for welding of smaller items such as internal tanks and structural assemblies. This general-purpose use of robotic welding is not yet standard practice in the shipbuilding industry.

Opportunities

Integration with the design process

In order to be successfully deployed in the shipbuilding process robotic welding needs to be integrated as part of a larger, comprehensive system that spans the areas of design, planning, and manufacturing. The process begins with the integration of welding procedures in the product model, where the joint types are initially defined. Here a rules-based approach could be employed to limit mating material types and sizes, and specify edge preparation procedures according to the detailed spatial configuration. The design must also take into account the particular access requirements of the robot in reaching the weld and maneuvering along the extent of the seam.

Changes in construction planning and scheduling

Robotic welding will require changes in the construction planning process. The physical access requirements of a welding robot will have implications on the placement sequence of piece parts during assembly and on the location and type of fixturing used. A welding robot is a large capital expense, but also has a very high duty cycle. In order to be utilized most effectively it needs to be constantly working. This requires careful scheduling and potential changes in the material flow and material handling processes to provide a constant supply of work. Maximizing the use a particular machine is a different kind of constraint than those normally faced by construction planners.

Cutting and material preparation

Robotic welding may also require adjustments in the manufacturing processes of cutting and edge preparation. Some automated welding equipment requires closer, and more consistent fit-up tolerances than those accommodated by manual welding. The seam tracking and bead weaving capabilities of the robot will determine the amount of variation in root gap, bevel, and surface finish that can be allowed.

Improved software tools

OLP software is meant to be a cost saving tool to minimize the robot down time associated with path planning. In the shipbuilding environment, characterized by low rate production and non-standardized part shapes, the overhead of robot motion programming can become a burden. OLP software is typically very expensive and requires a high skill level to operate. If every weld needs to be programmed separately without the benefit of reuse then OLP does not provide any cost savings. The software tools available for creating and managing robotic welding templates and macros are also highly specialized and difficult to use. In order to be cost effective for shipbuilding use, these robot planning tools need to be geared toward ease-of-use. They also need to be focused on rapid program modification and adaptation to support the low rate, custom part environment typical in shipbuilding. The ideal solution to these problems would be the automatic generation of welding paths and procedures directly from the geometry and material information contained in the design model.

Interoperability and standard data formats

Software tools for robotic welding form a very small market segment. These have typically been developed as proprietary solutions that are tightly integrated with a particular welding robot or as welding applications built on top of generic robot control programs. There are no standard formats defined for capturing welding information to be used in programs, or application programming interfaces (APIs) to aid in the development of welding routines. Templates used for programming a particular welding system cannot be easily applied to a system from a different vendor.

Reuse of skill and knowledge resources

Robots constitute a large capital investment in equipment and a significant human resource investment in the development of knowledgeable and skilled programmers and operators. It may not be practical to share robots between different application areas in the shipyard such as profile cutting and welding. However, there are obvious savings in the pooling of staff resources associated with robotics in all application areas. The robots used in welding are the same class of industrial robots that are used in other areas. The programming and operation skills used for one application will be almost entirely reusable in other applications. Due to the limited applicability of these skills, combining the resources of all those working on robotic applications may be the only way to sustain a viable group within an organization.

Specialized techniques for thick sections

Most of the automated welding systems in place in industry are doing straight line, single pass welding. In order to support the thick sections required for some naval structural applications, the capability for multi-bead, multi-layer (MBML) welding must be developed. Templates used for storing weld procedures would need to be modified to capture information regarding the sequence of weld beads and any weaving motions required. Automated tracking systems would need to recognize and take into account existing weld beads while following the joint. Robot motion would also need to be programmed to accommodate for the offset from the joint centerline at the large opening of bevels and any weaving or side to side motion required.

3. Testing/Inspection and Quality Control/Assurance

Background

As-built data management entails the processes for the collecting, analyzing, managing and publishing of data that describes the as-built configuration of a ship. It encompasses the areas of accuracy control and reverse engineering.

Accuracy Control is defined as measuring selected dimensions during manufacture, assembly and outfitting to allow in-process adjustments to assure the final product meets design requirements, readily fits to mating parts, and achieves system functional needs. The goals of accuracy control are to reduce the cost of manufacture, outfitting, and assembly; improved product quality; and minimize rework. Accuracy in cutting and fabrication reduces excess material and its costs. Measurement methods include tape measures and micrometers, laser scanning, digital photogrammetry (both with and without targets), theodolite stations, and CMM arms. Automated measurements that feed self-checks are the most efficient implementation of accuracy control.

The NSRP Benchmarking Report NSRP[2001] notes that European shipyards received high marks for their accuracy control processes. Self-checking is the norm and in general there is a high level of confidence in the dimensional accuracy of all components with the use of excess material minimized in most yards. However, US yards are relatively weak in accuracy control, even though accuracy control is generally recognized as a valuable means for eliminating unnecessary work. Self-checking and statistical accuracy controls are only used to a moderate level in a few yards. This means that most units and blocks go to the building ways or dock with excess material on at least one edge. They are then fitted at the building position, which is costly both in terms of direct man-hours and crane hanging times. The lack of accuracy in steelwork also has cost implications for the installation and connection of outfit systems.

There are emerging systems technologies that support two major as-built data management use cases: validation of as-built data to design (accuracy control) and capture of as-built data as constraints for new design (reverse engineering) or for build-to-suit. These two use cases have quite a bit of overlap; however there are also significant differences, which result in different technology requirements. In the validation use case, the objective is to determine whether an as-built work product conforms to the planned design. The overall use case consists of the following steps:

– Identify the critical measurements that need to be taken. In this use case the process of determining which are the critical dimensions is dictated by the design intent behind the as-designed product model. This applies whether the product model is a 2D drawing or a 3D digital model.
– Develop a plan for collecting the measurement data that has been identified.
– Collect and integrate the data. Collection of the data must be accomplished in such a way that it can be compared to design product model. The format in which the product model has been defined impacts the plan for collecting and integrating the data.
– Analyze the data and determine any corrective action that may be needed. Analysis of the data can only be accomplished by aligning measurement data with the product model data. This means that any tools developed to automate this analysis need to be able to process design data as well as measurement data.
– Evaluate results and establish lessons learned: The measurement data, the design data and the comparison of the two need to be stored and managed in such a way that they can be archived and accessed in the future – for example, to identify trends in similar scenarios.

In the reverse engineering use case, the objective is to collect as-built data so that it can be used to aid in the design of new work products that interface with the measured items. One example is the build-to-fit scenario, in which an item needs to be designed specifically to fit into an assembly or area of the ship that has already been constructed. Another example is in the overhaul process, in which design work does not start from a blank page but rather is dictated by the as-built condition of the ship to be overhauled. The overall use case consists of the following steps:

- Identify the critical measurements that need to be taken. In this use case the original design model is less important. In some cases it may no longer be accessible. The definition of the critical measurements is driven by the new items that need to be designed.
- Develop a plan for collecting the measurement data that has been identified. In some cases it is necessary to capture a complete model of the as-built conditions.
- Analyze the data and change it to a format that can be used in the new design. In this scenario the goal is to create a new design not to compare the measured data to an existing design. The requirement is to export design data rather than to import it.
- For build-to-suit, measurement data is analyzed to provide trade direction such as removing extra stock, sizing shims and building templates to ensure dimensions between adjacent components are achieved without rework.

One example is the ship check process for naval combatants. The goal of the ship check process is to acquire, manage and analyze information resulting from a physical examination of an existing ship.

State of the art

Traditionally the collection and analysis of as-built data has been a predominantly manual task. In many cases, it is still accomplished with tape measures. Even when automated measuring devices are introduced the process of transcribing and managing the measurement data is not fully automated. Today there is a range of data collection technologies available including theodolites, laser scanners, co-ordinate measurement machines (CMM) and photogrammetry. Each collection technology has particular strengths and weaknesses.

Theodolites

A theodolite system is an optical measurement system by which operators map and record data points to a computer for later use. The system uses a number of theodolite heads linked to a computer to triangulate the position of data points. This technology results in a very accurate measurement of individual data points, but is too time consuming to be used when a very large number of measurements are needed. A leading theodolite organization is the IMTEC Group. Details for this organization may be found at http://www.imtecgroup.com/

Laser scanners

A second data collection technology is *laser scanning*. Laser scanning is a convenient method for collecting a large number of points on a surface. A hand held scanner can be used to measure small objects; a mounted scanner is used for measuring a compartment's worth of data. A small number of targets may be used to enhance the quality of the measurement. Laser scanners capture a large number of data points on the surfaces of the objects scanned. This data structure is typically referred to as "point cloud." This approach is well suited to large, relatively smooth surfaces such as the hull of a ship. Recently there has been interest in the use of laser scanners for use cases such as ship checks. There are some limitations inherent in the application of this technology in this kind of scenario. The laser scanner only records data for surfaces that face the scanning device. Currently it is not feasible to capture surfaces that face away from the scanner or that are blocked by other objects. This limits the usefulness of the technology for applications such as ship checking. Another limitation is the difficulty of generating surface models from point cloud data. The conversion of points to surfaces is particularly difficult when the measured surfaces have many edges and other singularities. These are the conditions that are typically encountered when trying to capture an arrangement with a ship compartment. The volume of data (number of points) is too large to process in its own right; yet considerable effort is needed to interpret the data. The interpretation of the data can either take the form of fitting a mesh to the surface or of comparing the points to a known CAD representation. Both processes are, today, only partially automated and still require extensive effort. In some system the point cloud is used to assist an operator in the creation of a wireframe model. That wireframe model is then used to speed up the process of creating a solid or surface model. For data with few singularities, a point cloud can usually be converted fairly easily to a surface model. The problem is that most CAD platforms today deal primarily with solids, and there is no straightforward way to match surface models with solid models. For data with many singularities, the problem is to identify the edge and boundaries of objects. Today this is still a manual process. Information on leading laser products and services can be found at the following URLs:

http://www.inovx.com/home.html

http://www.cyra.com/home/home.html

http://www.solexperts.com/e-leica-totalstation.pdf

http://www.lewisinstruments.com/totalstation.htm

http://www.3rdtech.com/DeltaSphere.htm

Coordinate measurement machines (CMM)

Another style of measurement system employs the use of touch probes to measure inspection features related to a physical object. This approach is more discriminating than the laser scanning approach; it's objective is to enable meaningful comparisons to design intent or the creation of new design features. One family of such devices is the portable, measurement arm. These devices support the collection of a point at a time by means of touching the measured object. Although it represents an advance over the collection of measurement data with tape measures, there are some drawbacks to the approach. Even though it is based on the process of touching, it has difficulty measuring points and lines directly. A point is measured by touching the probe at the desired location. Of course, such an operation is subject to operator error; the probe may be placed slightly off location. This is compensated for by taking multiple measurements at the same point and averaging the result. Similar difficulties are associated with the measurement of straight lines. In many shipbuilding applications, the measurement of small number of strategically located points is all that is needed. For example, the size and shape of cut steel plate can be determined by locating its vertices. With a touch probe, this is best accomplished by finding the planes of the adjoining surfaces and computing the intersecting point. Leading measurement product information may be found at the following URLs:

http://www.faro.com/Default.asp

http://128.121.176.37/main/index.php

Close range digital photogrammetry

This approach has many similarities to the laser scanning approach. However, it is more heavily dependent on the use of targets. Pre-measured, known target locations require considerable set-up time. For scenarios such as ship checking, this set up time can be prohibitive. Photogrammetry is better suited for the measurement of a single object at a time or for scenarios in which targets can be set once and re-used for multiple measurements. For example, it may be used to detect variations in a manufacturing process that is supposed to be consistent for repeated instances. A second scenario entails the use of close range photogrammetry for measuring objects that have certain characteristics that simplify the translation of point data to meaningful inspection results. The big advantage of such a capability is that the set-up time is minimized and in some cases eliminated. Operator intervention, such as that required with a touch probe, is eliminated. This means that more items can be effectively measured and checked automatically without operator intervention.

Integrated metrology systems

Most metrology tools today are accompanied with their own software for managing, analyzing and storing measurement data. This has the advantage that the software can be tailored to the particular measuring device. However, there are drawbacks. Shipyards are required to learn and support multiple software packages, and interoperability between the software packages is very limited. A newly emerging approach is the integrated metrology software package, which is capable of acquiring data from any combination of collection devices. This approach has several advantages. First, there is a core set of functionality required for the analysis, management and reporting of measurement data. There is no reason the functionality has to be duplicated for each new type of measurement. A consolidated system simplifies the training and support requirements for the shipyard; a common user interface can be used with different devices. Moreover, such an approach supports the use of dynamic, collaborative sessions in which the measurements from various devices can be combined in a single presentation. Tool information may be found at http://www.mrcday.com/spatial_analyzer.htm

Technical challenges

Automation of the accuracy control processes relies heavily on the concept to the "point-reducible feature." A point-reducible measurement feature is a meaningful design abstraction that can be defined completely by one or more geometric points. A measurement feature consists of a geometric component, a description of design intent and information regarding acceptable tolerance. To a certain extent measurement features are constrained by the technology that currently supports their definition. Measurement results consist of measured geometric points arranged in a meaningful manner. One of the biggest technical challenges to the automation of accuracy control processes is the association of measurement features to the corresponding design features. As noted above, today's shipbuilding CAD systems do not support a systematic approach for capturing of design features. This is a prerequisite for automated accuracy control. Moreover, today’s metrology systems, even the integrated ones, each use their own proprietary feature set. An integral part of the accuracy control use cases is the comparison of measurement data to the as-planned product model. The accuracy control system needs to be able to represent both product model geometry and measurement geometry. Some systems make a distinction between points (from the product model) and targets (points collected from a measurement device).

A second technical challenge involves the ease of use of automated metrology tools. There are clear advantages to the use of advanced measurement devices over the use of tape measures and micrometers. However, in some cases the new tools are so difficult to master that their usage is limited. Today’s tools aspire to be general-purpose measurement tools. As such there is a burden placed on the operator to master a number of geometric principles. For example, the first step in many of today’s systems entails the reconciliation of the coordinate system of the measurement device to the coordinate system of the CAD model.

Another technical issue involves the availability of critical dimensions in the product model. Most automated accuracy control systems support a best-fit function that can align coordinate systems based on the manual selection of key points in the product model to key measure points. However, as noted above, today’s shipbuilding CAD systems do not provide an adequate capability for the capturing of critical dimensions.

Finally automated accuracy tools need to address the issue of uncertainty. Measurements are never totally free of error. The tool needs to be able to quantify the expected magnitude of such error in order to support meaningful comparisons to the product model.

Opportunities

This section describes some areas in which new systems technologies capabilities could improve the efficiency to the as-built data management processes:

Matching inspection features with design features

The ability to match inspection features with design features is a pre-requisite for the automation of accuracy control processes. There are actually a number of enablers that are needed to support this ability. First, shipbuilding CAD tools need to be enhanced to be able to capture an industry-standard set of design features. Work has begun in some disciplines such as piping and in the STEP shipbuilding standards, but in general the CAD industry does not yet support this requirement. In fact, the tools that support the importing of CAD geometry into metrology systems are inadequate. Many systems support only older data exchange formats such as IGES. Typically, only geometric data is imported. There is no way to relay critical information regarding design intent. It is often necessary for an operator to manually filter the imported geometry to remove a large volume of extraneous geometry.

In addition, metrology systems need to support an industry-standard set of inspection features. An industry standard set of inspection features is under development within the automotive industry by the Metrology Interoperability Consortium, and this work should be extended to support the shipbuilding industry. After the two sets of industry-standard features are implemented, there is the further requirement for a computer-interpretable means for associating instances from each set. The objective should be the creation of a product model in which each critical design feature is associated with an inspection which designates how the as-built condition of the reference should be measured and how the inspection results are to be compared with the design model. Care must be taken to keep inspection features loosely coupled to the design product model. Measurement features may vary from shipyard to shipyard and must remain separable from the design model.

Product data management for as-built data

In today's system measurement data is not adequately integrated with the design product model data. Measurement data is typically managed in file systems, often within documents such as word processing documents or spreadsheets, which are not linked to enterprise data management systems. Some metrology systems utilize database management system, but for the most part these are also isolated systems. In fact, measurement data is often treated as a transient, rather than a persistent asset. A point is located on the hull in order to accomplish an installation process, and there is no further need to store it. In order to get the full benefit from more sophisticated and more efficient as-built data collection, it is necessary to have the means to associate the measurement data with the pertinent design instances. In order to accomplish this, a full-fledged product data management capability is needed. On the one hand, the trend is that shipbuilding product model data is managed within some sort of PDM environment. The PDM environment handles such things as configuration management (including effectiveness), approvals, process control, work requests and work orders. These capabilities need to be extended to measurement data. There should be a capability in which measurement results (consisting of one or more populated measurement features) can be stored and configuration managed. The system must support references into the enterprise PDM environment so that measurement objects can be associated with the appropriate (configuration controlled) product instances.

General purpose vs. specialized inspection tools

Today's generation of measurement tools and systems strive to be general purpose, satisfying the broadest possible range of metrology needs. However, the general-purpose nature of these tools sometimes make them prohibitively difficult to use for simple and/or frequently repeated tasks. Many of the measurement tasks that are required in the shipbuilding industry can be categorized and specialized into a relatively small set of families of tasks. The shipbuilding industry should be proactively defining its specific as-built use cases. These use cases should become the foundation for a set of requirements that is presented to metrology system vendors as well as to international standards bodies.

A significant advantage of such a specialization is that some families of measurement tasks can take advantage of constraints inherent in the use case itself in order to simplify the task so that it can be more completely automated. For example, in today's systems, the accuracy control use case entails significant operator intervention to align the measurement and product co-ordinate systems. In some use cases there are sufficient hints in the procedure for data collection so that the co-ordinate system alignment can be computed automatically. Some systems provide programming macros that can be used to support such specialization. However, a more comprehensive and reusable approach would be to define explicitly a standard set of shipbuilding use cases and to provide functions to support each one.

A good case in point is accuracy control for the cutting of steel plates and the cutting of sheet metal shapes. Both problems are essentially flat pattern problems, and many simplifications can be exploited as a result. For example, a flat pattern is more amenable to digital photogrammetry. It is a much simpler problem to detect planar edges and vertices than the detect boundaries in three-dimensions. For this type of measurement, there is enough information already in the collected data to align the measurement and the design coordinate systems. In fact, it is conceivable that the process of assessing the accuracy of a cut steel plate or flat sheet metal piece can be totally automated. The piece is photographed; the image transmitted to the metrology system, which detects the edges and coverts the data to a set of measurement features. The system located the corresponding design model, which consists of the appropriate design features. The software analyzes both data sets and computes the transformation to align the coordinate systems – aligning the associated features at the same time. Each measurement feature is compared to its corresponding design feature. This approach has significant potential for eliminating set up time; the number of pieces that can be measured increases tremendously; there is a better opportunity for meaningful statistical process control. Without the simplifications that result from the special characteristics of the measurement task itself, many of those automated steps would not be possible.

Feature recognition from point clouds

Automatic feature recognition from point clouds has been a technical challenge that has eluded researchers for a long time. Nevertheless, automatic feature recognition is a pre-requisite for the effective use of point cloud data for the shipbuilding industry. As we have seen, processes that rely on measurement data can be automated only after useful measurement features have been defined and implemented. In the systems we have looked at so far, it requires either operator intervention or specialized restrictions that account for the creation of measurement features. 3D scanners use laser technology to capture physical objects such as structures or scenes and convert them into digital point cloud data (3D coordinates of points in the cloud relative to the scanner). This point cloud contains a huge amount of points and specialized software is required to manipulate and reduce the point cloud data to extract the feature. Technology currently exists to convert a 'cloud of points' acquired from laser scans into a simplified 3D model. This simplified model is a 3D surface model which is converted from the thousands of laser scanned points into an optimized CAD model, automatically. The surface model essentially 'connects the dots' with poly-mesh 3D CAD geometry. This optimizes the size and shape of the geometry by eliminating redundancy to significantly reduce the file size when compared to the original laser scan cloud. The accuracy of the 3D CAD geometry depends on the accuracy of the scanned point cloud data. The meaningfulness of this data is compromised, however, because of its lack of features. Today, the only way to associate particular points in the point cloud with measurement or design features is through tedious operator intervention.

Improved means for processing critical dimensions

As we have seen above, there is a recognized need to enhance shipbuilding CAD systems so that they represent critical dimensions. By the same token, automated accuracy control systems will need to be able to process these new data structures. Critical dimensions are an essential part of the algorithms that will be used to align measurement with design coordinate systems. Measurement data cannot be compared to design data unless both are situated in the proper context.

Visualization tools

Improved scientific visualization tools will be needed in order to take full advantage of digital as-built data management capabilities. It must be easy to recognize trends and ramifications from an examination of as-built and it's associated CAD data. Simple overlays are not sufficient. New techniques are needed that illustrate well such concepts as confidence intervals, critical vs. non-critical dimensions, and tolerances.

Standards for the interoperability of as-built data

As-built data will need to be interoperable with a number of other systems, including CAD systems that represent the as-planned model, various metrology systems that need to integrate the date, product data management systems that coordinate and manage configuration of the data, and logistics support systems that rely on as-built configuration data. Today there are no such standards. Measurement data is 'shared' only by exporting text files in non-standard formats. The National Institute of Standards and Technology (NIST) has begun work on an ISO-STEP standard for the representation and sharing of inspection and measurement data. The work is being done by the Dimensional Inspection Information Exchange Project. The plan is to produce an international standard (ISO10303-219) which integrates with the STEP product data models, such as those that support shipbuilding. This work has been sponsored so far by the automotive and aerospace industries. The U.S. shipbuilding industry should support this activity and ensure that its special requirements are addressed in the international standard.

Build to fit/reverse engineering

Digital as-built information can also be used for build to fit use cases. In order to support this capability tools need to be developed which can convert measurement data directly to a usable CAM format. In the short term this would mean the generation of M&G machine code from measurement data. In the long term measurement features could be used to generate new design features. These design features would be used in applications such as STEP-NC controllers to automatically generate CNC work plans.

4. High-Level Resource Planning: ERP Capabilities (SAP, Oracle)

Background

This section describes the requirements and capabilities of Enterprise Resource Planning (ERP) systems for the shipbuilding industry. ERP is a critical capability for the shipbuilding industry. ERP entails the management and control of shipyard production processes at virtually every level. This includes material management (from purchasing to inventory control); work planning (from schedules to work orders); personnel (from resources to qualifications); and as-planned product data (from bill of material to the management of joints). As with other systems technologies that we have examined, the shipbuilding industry is in the unfortunate position of having special and extensive requirements but only a minor market share among ERP vendors. The first generation ERP systems were oriented toward process industries and repetitive discrete manufacturing processes. The production processes in the shipbuilding industry are built to order processes. Moreover, there is very little repetitive manufacturing. Even though many ships are instances of a class, there is a substantial interval between the repetition of a task on each hull. In that interval it is not unusual for design or production changes to have occurred. The shipbuilding production processes are more akin to construction processes than to the repetitive processes found in the automotive industry. Support for these kinds of processes have eventually been incorporated into ERP systems, but they are not always aligned with the original functional capabilities.

ERP systems seek to cover as much ground as possible and, thus, support a number of different production processes and business processes. These include:

Bill of material (BoM): The ERP system manages hierarchical structures of items.

These items are most often the component parts of the ship, but they could also be equipment, functional locations, documents and sales orders. For each item, the BoM designates such data as name, quantity, and unit of measure. The BoM supports material management, staging of material for production and costing – for new construction as well as for maintenance.

Master planning: This function defines production quantities for stated intervals. This includes material forecasting (using known rates of consumption to forecast needs), demand management (defining future requirements for finished products), master production scheduling (marking certain parts for special schedule attention), and long-term planning. These are the functions typically associated with master planning in an ERP system. It should be clear that there is not a good match between the provided capabilities and shipbuilding processes.

Capacity planning: This function established available capacities in relation to production requirements. Capacity planning can be computed for long-term, mid-term or short-term planning. It consists of scheduling, calculating capacity loads, evaluating capacity and leveling.

Material Requirements Planning: This function supports the availability of material for sales as well as for production. It deals with monitoring and replenishing stocks by scheduling timely purchasing and production, usually by automatically creating purchase orders or work orders.

Production Orders: This function is also known as shop floor control. It provides the specification of what is to be produced and on what dates. It also designates locations and costs. It also provides the means to associate a routing with a work order. Subsequently, the BoM is exploded, and material and resources are reserved. It determines planned costs and identifies non-stock components and external requirements.

State of the art

Today one vendor dominates the ERP domain among shipbuilders. Even though there are a number of well-established ERP vendors (including Oracle), most shipyards are leaning toward SAP as the favorite. Currently, every major shipyard has an ERP/MRP capability. Some are highly-customized MRP systems. These systems are typically built on technology that is dated and is cumbersome in many respects – from the underlying programming language to the database technology. Such systems are difficult to extend and interoperability with such systems is not well supported. The problem is that such systems, as a result of considerable customization, now meet the functional ERP needs of the shipyard. Experience has shown that the deployment of an ERP capability at a shipyard is a monumental undertaking, and its success is by no means assured.

Deployment of an ERP capability is complicated by a number of issues, including the lack of competition, the extensiveness of ERP functionality and the need for the integration of several capabilities in order to support ERP needs. In addition, ERP systems support mission-critical functions within the shipyard. As a result, even though there is a single vendor that is generally preferred, there are still hurdles to successful deployment. These hurdles are both technical and cultural. On the technical side, the SAP application, because of technical as well as competitive drivers, is a monolithic system built upon a single common data model. Its modules are tightly coupled with each other and, thus, discourage the use of modules from other vendors. The scope of the application is very broad, and the prospects of significant changes to the existing code base are slight. The tool itself imposes certain processes on the shipyard, and as we have seen, the processes that come out of the box do not always provide a nice fit with shipbuilding requirements. For example, the configuration management capability in SAP provides considerable capabilities to support variants and production of lots. Configuration management requirements for shipbuilding do not make much use of these capabilities. In the end, the shipyard must either change its process to accommodate the ERP system or jerry-rig a solution that bridges the gap.

Another problem with current ERP capabilities is the lack of standards that support information sharing to and from the ERP system. Ten years ago the same problem faced CAD systems, but steady progress in the STEP arena has changed that. The situation is not as promising for ERP information sharing. One factor has been that the information in the ERP system is viewed as less re-usable than the design product model data. There are fewer potential users of, say, a work order than of a system diagram. Another factor is that there are so few ERP vendors. The argument can be made that there is less need for information sharing. Nevertheless, there have been some efforts to standardize the sharing of ERP information. Most of this activity has taken place in the context of business-to-business e-commerce. The first generation standards were EDI and EDIFACT. Both of these standards emphasized business transactions as well as information sharing. As a result the standards became bulky and expensive to deploy. Most shipyards have looked at the standards, but they have not been widely adopted among the U.S. shipyards. The current activity is focused on the development of an XML- and Web-based approach to e-commerce. Today most shipyards have invested in non-standard solutions. Several competing proprietary XML business languages have been proposed; some industry consortia have been formed to promulgate industry-specific languages.

Currently, the most active group addressing e-business standards is the Organization for the Advancement of Structured Information Standards (OASIS). OASIS is a not-for-profit, global consortium that drives the development, convergence and adoption of e-business standards. The OASIS consortium employs an open process by which its members promote industry consensus and attempt to harmonize disparate efforts. OASIS produces de facto worldwide standards for “security, Web services, XML conformance, business transactions, electronic publishing, topic maps and interoperability within and between marketplaces”. One of the standards being developed is the Universal Business Language (UBL). The purpose of the UBL is to provide a standard library of XML business documents (purchase orders, invoices, etc.) by modifying an already existing library of XML schemas. UBL is intended to become an international standard for electronic commerce freely available to everyone without licensing or other fees. However, like its predecessors, UBL is currently focused on business documents, including purchasing documents, materials management documents, payment documents and catalogs. The focus is on business-to-business interactions. In order to support full ERP interoperability, the focus would have to expand to cover internal documents: work orders, schedules, plans, routings, etc.

One of the most ambitious ERP activities in the shipbuilding domain is the US Navy's NEMAIS project, the US Navy Enterprise Maintenance Automated Information System. The objective of the NEMAIS project is to provide ERP functionality across the fleet and regional maintenance centers. The goal is to replace the multitude of systems that are currently in place. The technical approach is to deploy a SAP system across the participating organizations. Consequently, the first step of the deployment is the standardization of the processes at each organization. The standard process must be aligned with SAP capabilities. This represents an attempt to deploy an integrated approach (rather than interoperable approach). The idea is to enforce the use of a single system using a shared database with a single information model. One of the requirements of the NEMAIS plan is that it integrates with legacy systems, notably with the ERP systems at the shipyards. At this junction, there will be a requirement for ERP information interoperability. Currently there is no technical plan regarding the form that such information will take.

Opportunities

Modular ERP capabilities

The current generation of ERP systems is built on the philosophy of integration as opposed to interoperability. When those systems were built, the only viable technical approach for uniting various applications was by means of a tight integration. This approach had the advantage that it was the only one that worked at the time, but its disadvantages are that the resulting monolithic system is unwieldy. It is difficult to modularize such an approach and make it work with other vendor's products. It is difficult to integrate such a system with other tools that are used throughout the enterprise. Recent advances in information interoperability have changed the landscape because enterprise application integration can be implemented in a more flexible way. Because ERP functionality is so pervasive and so essential to the operations of the shipyard, there is a need for more modular ERP capabilities. This approach would facilitate the sharing of work among shipyards as well as the deployment of ERP capabilities to smaller shipyards. Moreover, a more modular approach supports the process of adopting newer and more powerful information technologies throughout the shipyard.

Interoperability of ERP and life-cycle support systems

The current generation of ship designs has been captured in digital product models using Integrated Product Development Environments. More and more, these product models are based on design for production strategies; however, the technology for communicating this information to construction and support services is lacking. The result is that the full benefits of the product model are not always exploited.

The need exists for tools to support the sharing of ERP data that support production processes as well as life-cycle support information. This should include interoperability with the product model data as supported by the NSRP/ISE project. The technical approach is to build upon the successes and architecture of the ISE project. This work should utilize international standards such as those being developed by the Product Life-Cycle Support (PLCS) team.

The tools for ERP interoperability would include tools to support the following life-cycle support activities:

- Shared work packages across organizations. The Navy has undertaken several initiatives (in particular, the NEMAIS project) to deploy ERP capabilities through the Navy infrastructure. Although much of this work centers around a particular ERP product, there will still be requirements for an open exchange of work package information. This requirement is even more pressing when work is shared with shipyards or other organizations that have not deployed the enterprise system. There is significant overlap in the information requirements for initial construction and MRO. The tools developed here would be fashioned to support the sharing of work packages in both scenarios.
- Integration of product model data into life-cycle support processes. Currently life-cycle support is heavily dependent upon drawings and document-based change orders. There is a need for re-engineered processes that make more direct use of the product model.
- PDM data typically is used to initialize as-built and as-maintained product structures. There is a need for tools to automate this process. New process opportunities should emerge as a result of more accessible PDM information.
- Today technical manuals are published in SGML, but the trend is clearly toward XML. There is a need to develop tools to integrate the product model and other support data with XML-based technical manuals.
- Systems diagrams are an integral part of the life-cycle support process. There is a need to make it possible to share piping, electrical and HVAC diagrams with users on the delivered ship.

As-built and as-maintained product models

By providing interoperability between the design/construction shipyard and the maintenance activity as-built and as-maintained feedback can be provided and captured in the product model enabling 100 percent configuration management. Resultant benefits include:

- Aid in the development of standard work packages across private and public shipyards
- Eliminate the requirement to perform expensive shipchecks

– Enable the performance of more accurate design studies
– Enable accurate estimates for modernization of shipboard technologies
– Provide the ability to remotely plan maintenance activities
– Provide more accurate asset visibility
– Enable real time downloads of logistics products that reflect the most recent configuration changes for maintenance activities.
– Support more accurate supply support

By providing interoperability among design/construction shipyard systems, the planning aspects of co-production are supported and can be extended to the ship maintenance, repair and refit processes.

5. Process Mapping and Simulation

Background

Process Mapping and Simulation involves the use of specialized software tools for modeling the behavior and interaction of objects and process steps in a time domain. Traditionally software tools were either good at process mapping or process simulation, focusing on knowledge capture or process analysis, respectively. Today, most process mapping tools have either incorporated a simulation routine or provide a link to third party simulation software. While process simulation tools have enhanced their capabilities to also capture additional process details simply for recording knowledge and are not necessary for simulation. Process mapping and simulation tools are typically used to explore what-if type analyses, comparing "As-Is" to "To-Be" processes, feasibility analysis of planned conditions, or in the planning of proposed implementations.

Process mapping is most commonly used for process improvement initiatives and knowledge capture. Tools support various process mapping methodologies and techniques, such as IDEF and Value Stream Mapping. IDEF focuses on knowledge capture and provides a standard format to capture and represent process details. While Value Stream Mapping best supports process improvement initiatives by clearly illustrating value-added vice non value-added process steps. Most process mapping tools are flexible enough to support various methodologies and techniques.

Discrete Event Simulation is typically the tool of choice for process simulation. In these simulations, the time associated with a particular event is described by a random selection within some distribution of possible time values for that event. Time taking events can represent the activity of a machine or operator performing a process step, or the movement of objects between different locations. Elapsed time can also can also occur due to a queue or buffer. Events have fixed dependencies, such as “process B begins when three items of type A are present.” Multiple objects and process steps are combined into a composite model that simulates the performance of some real life task or process. Material can be added or removed from the model at any location to represent the flow of different products through the process steps. Each time the model is executed it yields a slightly different result time, which falls within a range of possible results. The model also keeps track of the amount and location of material over time. After running the model a number of times, statistical analysis can be used to characterize the simulated result times and material quantities at every location.

The use of process simulation software tools allows the model to be easily modified to represent either desired or unexpected changes to the process being studied. The model can be used to simulate the introduction of new machines or process steps to an existing operation. It can also be used to perform what-if scenarios to determine the effects of machine breakdowns or stoppage in material flow. These changes can be easily accomplished through parameter settings in the software model and the results can be obtained quickly by re-executing the model.

Four different types of analyses are performed by process simulation software. They are scheduling, resource analysis, material flow, and capacity planning. Although dedicated scheduling and schedule optimization software exists, process simulation is sometimes used to investigate the feasibility of a proposed schedule or in the development a project schedule. A schedule can be generated by using the resulting simulation data, along with the project event dates. Resource analysis is the use of a simulation tool to analyze the utilization of resources – machines and labor – during a given operation. High utilization of particular resources may be an indication of a bottleneck in the overall process, thereby identifying the potential need for large capital items. Low utilization can be an indication of redundant resources or inefficiencies in the process. Large cycles in utilization can point to critical events such as deadlock conditions or extended waits for a single resource such as a crane move. Process simulation can be used to study material flow. The amount and location of all material, both source and product, is tracked continuously. As the simulated operation progresses it is possible to see trends in supply and demand at different locations. The effects of changes in material availability and distribution speeds can easily be determined. Another related analysis is that of capacity planning. Here the desired model is established and run against a fixed or best-case schedule for a given period of time. The overall output of material during this set amount of time gives a measure of the operational capacity. The model can then be optimized to determine the maximum process capacity or whether a particular capacity level can be achieved.

State of the Art

There are no process simulation tools available that are dedicated to the shipbuilding industry in particular. A wide variety of process mapping and simulation software is commercially available. Software packages span a broad range in both cost and capabilities. Process mapping tools are relatively inexpensive and user friendly. The more expensive packages include animated graphical output, sophisticated statistical analysis capabilities, and built-in optimization routines. Creating animated process simulation models requires a person with skills in the general field of process modeling or operations research, and a detailed knowledge of the simulation software being used. Process mapping and simulation also requires individuals with subject matter expertise

in the specific process or task being studied.
In addition to process mapping and simulation, the available software tools possess some other interesting capabilities that have yet to be exploited in the marketplace. These additional capabilities include various optimization engines, a schedule generator, machine process control, software application development, and electronic workflow. In some instances the tools with these additional capabilities evolved to include process mapping and simulation, and not the other way around.

One of the process simulation tools that has been used in a number of shipbuilding applications is ProModel, from ProModel Corporation. NASSCO has used ProModel to study resources, material flow, and capacity planning at their San Diego shipyard. The panel line process was carefully modeled to evaluate resource utilization. Simulations using this model indicated certain inefficiencies in the existing process. Changes to the process were introduced in the simulation model to study their effects. As a result, changes were made in the actual panel line process, which improved overall efficiency. The shipyard is tightly constrained by surrounding property and occupies a relatively small footprint. Material flow through the plate yard and panel line was studied to determine if any improvements could be made through changes in the layout of the yard and material transport. Since the shipyard could not be expanded physically to meet potential increases in product demand, capacity planning was used to determine the maximum output possible based on the current size. ProModel proved to be quite capable in performing all of these process simulation and analysis tasks. This overall simulation effort was completed as a team effort between NASSCO shipyard staff and outside consultants with expertise in process modeling and simulation.
Another process simulation software package that has been demonstrated in shipbuilding is QUEST, from Delmia. QUEST has been used to predict capacity and specify material flow for a new steel processing facility. Before the new facility was built, process simulations were performed to determine the expected throughput of the new plate cutting machine and material handling equipment. These results were used in arriving at the detailed machine specifications. Simulations were also used to determine the optimum flow of material to the cutting machines and between multiple lanes within the facility. QUEST provided all of the modeling and analysis functionality required for this work.

Lean manufacturing initiatives have stimulated the use of process mapping and simulation tools. The tools have provided a quick means to analyze the difference between current and proposed process change. Extend software is a two dimensional process modeling and simulation tool that has been used to demonstrate labor and span time savings associated with the process of welding hull butts. Significant savings were recognized from modeling and were later validated with the implementation of the new process.

Opportunities

Standard for process data definition

One of the difficulties with process simulation is that there is no recognized standard for capturing or exchanging process information. Process models that are created using a particular software tool cannot be readily transferred for use with other software tools. This limits the possibility of reuse of process models and creates a barrier for the spread of process knowledge throughout and between organizations. Work is underway at NIST to address this problem through the creation of an information model for processes. The Process Simulation Language, PSL, is intended to define the data elements of process knowledge and to provide a neutral format for exchanging process data between applications. The shipbuilding industry can help in this effort by extending PSL to include shipbuilding specific process information and by supporting pilot data exchange projects.

Ease of use

The work of process mapping and the use of process simulation tools require a high level of skill and detailed knowledge. There needs to be subject matter knowledge of the process being modeled, an understanding of the field of process capture and process modeling, and a detailed knowledge of the simulation software used. Although these knowledge requirements may not be able to be eliminated, there is an opportunity for the development of simplified user interfaces to process simulation. More work needs to be done in order to allow the end user to define and control the simulation without being an expert in process modeling or simulation software

Process knowledge and management

Traditionally shipyards are good at managing products and the associated sub-processes, but have a limited vision of the global or cross-functional processes. Process mapping provides a means to capture process data at all levels within an organization. Even though hierarchical model building is prevalent in many tools, few provide a good means to obtain aggregate data at higher levels. There can also be some improvements in the way these maps are documented, published, and linked. Also, schedule and resource data are not electronically linked to procedural information. The simulation capability associated with an optimization engine can be used to generate shop floor schedules based on current conditions; resource availability, machine down times, or procedural changes. Using the same simulation/optimization engine, higher level analyses could also yield resource requirements based on products and events. This could support manpower planning (training, hiring, or re-allocation), and capital expenditures.

Process controls can also be derived from these tools since they capture routing, actions to performed, and span times. Therefore an opportunity exists to automatically create electronic workflow systems based on process mapping and simulation data. In addition some more work could be done to link these tools with machine controls to provide the data they need to perform their functions. Both applications would also provide the feedback necessary to better measure and control processes.

6. Lean Manufacturing

Background

Traditional shipyard process improvement programs have often concentrated on increasing the efficiency of individual manufacturing operations (e.g., more widgets per hour from a given machine, reduced process lane cycle time, better welding techniques, etc.), where most of the focus is on improvement of <u>touch</u> labor performance. Lean Manufacturing, on the other hand, a body of knowledge which originated in the Toyota Production System (and which is also generically called Lean Enterprise when applied "above the shop floor"), is a total business process improvement strategy and suite of tools/techniques centered around the elimination of "non-valued-added" (waste) activities from an entire business' "value stream". Central also to the Lean philosophy is the pursuit of continuous, single-piece flow of material through the manufacturing process and "pull-based" process triggers for material movement and individual manufacturing activity starts.

A key distinction of the Lean approach is that defining what constitutes a "value-added" activity can only be done from the paying-customer's perspective. Value-added steps, therefore, are only those activities that change form, fit, or function of raw material into the finished product, or, in the case of ship design activities, those activities that add maturity and fidelity to the engineering design data. Because, by this definition, most business activities (as much as 90-95% in a typical American corporation) are actually non-value-added waste, the Lean techniques and tools focus primarily on ways to "see" waste during the "document the current reality" phase, and on ways to eliminate waste in the "improve" phase.

From the perspective of the CAD-CAM-CIM environment, which would only be a small subset of the Lean "tool box", such waste analysis tools would include functionality related to process mapping and simulation (see the prior section in this paper for the simulation-related discussion), statistical analysis, data mining, and enterprise cost analysis. In the manufacturing improvement end, however, the support required to implement Lean could be related to almost any of the CAD-CAM-CIM tools, including: enterprise resource planning, scheduling and simulation, collaborative workspace technologies, visualization, product data management, manufacturing tooling software, etc.. Because Lean improvements can require such a smorgasbord of solutions, only those tool areas specifically related to "seeing waste" and those areas related to "pull-based" process triggers are addressed in this state-of-the-art report.

State of the Art

In companies that are successful in implementing Lean, most process improvement activities are done in a team environment on an "event" basis; that is to say, the right players are pulled off-line, placed in a room for a week or two, given a skilled facilitator who is trained in Lean (and often Six Sigma) techniques, and told to hash-out a complete solution, end-to-end. This "this is serious" mentality, coupled with the pressure of a pre-scheduled executive out-brief, dictates that the analysis tools used by the teams must be quick and dirty and support rapid decision making based on the best available data. Process mapping is a central exercise in these team events, so markers, sticky pads, and plotter paper (manual methods) become the order of the day. Process mapping software, when used, is usually a luxury, but in very complex projects can become an outright necessity. Because of the need for speed, ease of use of such software is paramount, but is not often found in today's software tools. General Dynamics – Electric Boat has used Extend (ImagineThat, Inc.), VISEO (Microsoft), and even simple Microsoft Powerpoint slides for documenting process maps, with the more complex packages utilized when numerical modeling and simulation is required. The more complex tools require specially trained users, which can be a scarce resource when many Lean teams are deployed simultaneously.

Lean Manufacturing/Enterprise teams also have to quickly analyze large amounts of cost, schedule, and product data about manufacturing and business operations to determine root causes of waste, rework cycles, and defects. The purpose of these analyses is to justify, in bottom-line, dollar and cycle-time savings, where to invest in new technologies and processes. Because lean (enterprise) methodology is focused on incremental change, it has a built-in bias against revolutionary change. The focus is on eliminating unneeded, wasteful steps. This type of change does not emphasize knowledge of available systems technologies, which is the source of revolutionary process changes. Today, most of this shipyard cost, schedule, and product information resides in legacy, often proprietary (and sometimes stand-alone) databases, of any manner of sophistication, and can be hard to extract and interpret in the manner desired for a given unique analysis, even by skilled users. When data is found to be available and is extracted in a usable form (usually simple, tab-delimited text extracts), statistical analysis software is utilized. This analysis software can sometimes be as simple as Microsoft Excel (with statistical "Add-Ins"), but highly capable and specialized applications are also used when both the software and skilled statisticians/users are available. A number of statistical analysis software packages have been developed explicitly for Lean and Six Sigma applications (including such esoteric requirements as Design of Experiments and Response Surface Modeling) by the leading consulting firms in the field; most of these products are available for general public purchase.

In the Lean "improve" phase, "pull" systems are ultimately pursued to draw material through the manufacturing cycle based on a "backward" flow of triggering information (i.e., from a customer demand, reverse sequentially toward the very first manufacturing & material ordering steps). This single-piece-flow, "pull" philosophy (versus a batch, "push" approach), is demonstrated to dramatically reduce work-in-process, rework costs, and *Takt* time (the rate at which a process can meet customer demand). Pull triggering systems (also referred to by the Japanese word: *Kanban*) can be as simple as min-max inventory control cards, painted floor squares, and *Andon* (status) lights, or could be as sophisticated as integrated process flow and process control software. As of this date, we are unaware of any US shipyard applications that utilize such integrated process control software, where manufacturing operations within that system are based on the “pull” approach.

Opportunities

Opportunities exist to provide Lean practitioners with easier-to-use process mapping software, capable of quickly generating functional (“swim-lane”) process maps with composite cycle and touch time predictions/simulations. (Such software should be intuitive to use with little training.) Data mining applications with integrated statistical analysis tool suites and decision support systems that could reach across platforms and legacy systems would be particularly useful in providing a myriad of insights about shipyard operations and improvement opportunities. ERP systems which could feed integrated process control software for local pull triggering with visibility at a program level for bottleneck analysis would be particularly helpful. And, perhaps most importantly, as, what is measurable gets measured➔what gets measured gets managed➔what gets managed gets done…flexible, activity-based cost accounting systems with objective schedule progressing, not solely based on DoD-driven cost accounting practices (i.e., independent of Earned Value Management Systems), would drive process improvement decisions to “Investment Thinking” levels on and improvement-by-improvement and enterprise-wide basis.

7. Rapid prototyping (RP) technologies

Background

This section describes rapid prototyping technologies. Rapid prototyping (RP) is the process of creating a physical, solid (3D) model from a computer-based model representation. The RP model is made of different kinds of materials depending on the particular process and technology. In fact, material type is the main discriminator for the limitations and capabilities of the different technologies. RP materials include plastic, wax, laminates and metal. Even though it is a physical artifact, the output of the RP process is still a model. Its main contribution is as a simulation, not as a finished work product. The goal, then, as with any other simulation, is to gain some benefit from the model. Moreover, it must be possible to create an RP model very quickly and very inexpensively. All RP technologies strive for this goal; each one is generated directly from a CAD model with no intermediate processes required. Nevertheless, some of the technologies are more economical than others.

RP technology is actually more of a publishing technology than a modeling technology. The assumption is that the model already exists in digital form. The RP model is one particular view of this model. The RP view is based solely on the geometry of the CAD model; no design features are passed through. The RP model is based on a facetted representation of the CAD model rather than an ‘exact’ representation. Such a model can be generated from virtually any 3D CAD platform. The data is typically transferred to the RP process via a VRML file format or *.STL file format. As a publishing technology, RP can be evaluated relative to other styles of publishing – from 2D drawings to an actual physical mockup to an individual CAD session to a visualization (either on a terminal or to a printer) to a virtual reality session.

Usage scenarios

The challenge is to find a usage scenario in which the RP model is more useful or more economical than the competing styles for publishing the product model. Unfortunately, the technology is not well suited to shipyard manufacturing needs – for structures or for piping. Current modeling capabilities are sufficient to perform static interference checking on such models. RP technology is not well suited for interference checking of space envelopes because the RP model best corresponds to final product configuration. There are, however, two usage scenarios where the RP technologies show promise: conceptual design modeling and dynamic interference checking. Even the early RP technologies are well suited for conceptual design modeling. In this usage scenario a CAD system is used to quickly create a model for a new ship concept. RP technology is used to generate a small-scale model that can then be used in presentations and discussions about the new concept.

A more promising usage scenario is dynamic interference checking. The outfitting and assembly phases of ship construction entail the movement of large components through tight, dense spaces. A digital model has difficulty modeling the physics of this situation. Even static interference checking is very computationally intensive; dynamic interference checking of a component as it is loaded into a ship is even more so. Moreover, the modeling of such kinematics is time-consuming and difficult. However, the RP model naturally incorporates the physics of interference checking. A section or compartment of the ship can be published as an RP model (at any stage of completion). The component to be loaded can also be published as an RP model. Loading paths can then be simulated by using the RP models. Interferences become readily apparent in such a simulation. When RP technology is cheap enough and fast enough to publish such models on demand, the RP models represent valuable tools for effective and practicable outfitting plans.

State of the art

Stereolithography

Stereolithography was the earliest RP technology. It uses lasers to harden liquid polymer material into solid form – driven by a digital CAD model. Because of the line of sight limitations of the lasers, there are some limitations on the kinds of geometries that can be supported. Stereolithography models are very accurate and durable; however they can be prohibitively expensive to produce. Other approaches have followed, trying to overcome some of the cost and/or geometry limitations. One such approach is laminated object manufacturing, which builds up layers of adhesive-coated paper to make a laminated model. Another approach is fused deposition modeling, which is based upon an extrusion approach.

3D Printing (3DP)

The most promising new approach for the shipbuilding industry is 3DP. This approach has no limitations on the geometries supported and is extremely fast and inexpensive. In this approach a powder-based plaster and resin material is hardened into a solid shape. Though the quality of the model is not suitable for a finished product, the accuracy of this approach is adequate for modeling purposes. Most important the hardware technology for this approach is based on commercial-off–the-shelf components for printers.

Opportunities

Dynamic interference checking

The 3DP approach has the potential to support the dynamic interference usage scenario and could very well become a valuable tool for planning of ship outfitting and construction. The technical issues that need to be addressed are whether the technology could support models of the complexity found in a typical ship's compartment. In addition, it must be demonstrated that such models can be generated substantially cheaper than the cost involved in creating the same kinematic model.

8. Visualization

Background

Visualization is the use of computer generated 3D models to display ship arrangements or detail representations of components. The 3D models are typically based on CAD design data that has been electronically translated into a format suitable for viewing. The models can be viewed on a desktop computer, workstation or projected on a large screen for full-scale viewing and group collaboration. Visualization can be used throughout the design and construction phases of ship production. It is used for rapid evaluation of concepts during the early stages of design creation, for design review during detailed design, for assembly planning, and for pre-work familiarization during construction. Computer generated visualization can serve as an electronic mockup, allowing designs to be seen, analyzed, and operated without the need for scale models or test platforms.

Visualization is being used in the U.S. shipbuilding industry on all major naval design efforts. The use of visualization in commercial shipbuilding and on smaller design projects is less widespread. A variety of software tools are available to support this work, both special purpose computer graphics tools and integrated graphics modules in naval architecture and CAD packages. Visualization is being used primarily as a design review tool, allowing arrangement walkthroughs and interference checking, at all phases of the design process. Visualization is also being used as a planning and validation tool for construction assembly and facility use planning. It is also used in specialized applications such as ergonomics and evaluations of human factors and display of maintenance and repair scenarios.

State of the Art

The high end of visualization capabilities in the shipbuilding industry is equal to the state of the art in other industries. The systems in place to handle visual review of design data for the Virginia submarine program, CVNX carrier program, and LPD17 support ships are at least as sophisticated as those used in the aircraft, automotive, or AEC industries. These large ship design projects manage greater amounts of graphical data than all but the largest plant construction projects. Specialized graphics computer hardware is required for very large models, but the recent advances in commodity PC hardware have made reasonable visualization capabilities available on most desktop computers. Dedicated software packages are available for capturing electronic motion pictures and publication quality images when this is required.

Visualization tools can be separated into two categories based on their integrated usage with the underlying CAD system. In one class there are visualization tools that act as direct extensions to the CAD program, as though they were another module of the same software used for design creation. At the most basic level nearly all CAD programs in use today have some capability for model visualization built in. Programs that model objects as 3D solids can be set to display the current scene with the visible surfaces shaded and hidden lines removed, to provide a reasonably realistic view. A more sophisticated approach in these integrated tools is to launch a separate rendering or viewing program from the CAD environment. The current geometry model is translated from its CAD representation to a lightweight format suitable for rapid display and transferred to a separate viewer. Examples of this CAD/Viewer integration would be the connection of CATIA V4 and 4D Navigator, or CATIA V5 and DMU Navigator, from Dassault Systemes. This integrated approach has the benefit of maintaining a single (CAD) data store for both design and visualization functions. Integrated viewer can be slow for very large models because the detailed product model data must first be retrieved in the CAD system and then translated for viewing.

The second category of visualization tools are those that work as standalone programs, independent of the CAD system. To support independent use these viewing tools must maintain separate data stores. This requires the use of data translation programs to move files between the CAD and visualization realms, and carries the added burden of data management for these separate files. The benefit gained by maintaining a dedicated store of visualization data is speed in retrieving large amount of data. For very large scale visualization this optimized performance becomes an overriding concern, and model retrieval time is a limiting factor. The three major commercial software products used for industrial visualization tasks are dvMockup from Division/PTC, Envision from Delmia, and VisView/VisFly from Engineering Animation Incorporated (EAI).

Northrop Grumman Newport News (NGNN) has a long history of 3D model visualization for ship design, beginning with the VIVID program. The current design work at NGNN on the next generation aircraft carrier, CVX, makes extensive use of two different visualization tools, 4D Navigator and dvMockup. The 4D Navigator viewer is integrated with the CATIA CAD environment. It is used for small to medium scale design review, running on the same engineering workstations used for CAD. DvMockup is used for large-scale design reviews and runs on specialized graphics workstations and graphics supercomputers. Visualization with dvMockup relies on a dedicated model store that is translated from CAD into a special format for viewing. Functional modules within dvMockup enable interactive and scripted walkthroughs, collision and clearance detection, evaluation of kinematic mechanisms and part motion, and ergonomic analysis.

The Virginia submarine program at General Dynamics/Electric Boat (EB) has made extensive use of the IGRIP and Envision tools from Delmia (formerly Deneb Robotics). The Envision tool is also used as the primary visualization tool on the LP17 program at Northrop Grumman Avondale. The use of Envision in these two design programs relies on dedicated data stores translated from the CAD source. Visualization is done on large scale sections of the ship arrangement using dedicated graphics workstations and supercomputers. The functionality available includes walkthroughs, collision detection, part motion and kinematics, ergonomic studies, and integration with time-dependent simulations. Visualization is used for design review and verification of assembly planning and construction sequences.

Opportunities

Data management and integration with design PDM

Large scale visualization systems typically make use of dedicated data stores that are independent of the CAD source models. Managing this data and maintaining consistency with the CAD product model data is a difficult task. Each visualization tool assumes a different data storage architecture, optimized for logical file maintenance and model retrieval performance. Ideally the visualization data could be managed in a PDM system similar to that used for CAD data management. This would require integration between the visualization and PDM software, and tuning of the PDM system to enable the highest performance in retrieval of large numbers of model files. Another area of integration between visualization and PDM systems would be the ability to dynamically query back and forth between the viewing and data realms. The graphical display could enable a query from a particular object ("click and discover") to retrieve non-graphical part data such as system designator, material properties, or vendor information. As a corollary, the PDM interface could allow standard SQL queries based on system, ship location, or part name to retrieve a desired arrangement view.

Integration with MRP and construction data

Most visualization systems in use in the shipbuilding industry are based on CAD design models and are organized according to the design product structure and design bill of materials. As design parts are rolled up into assemblies and build units during the planning process and organized into a construction bill of material the associativity between the original CAD parts and shipyard consumable parts listed in MRP can be lost. In naval shipbuilding, where each hull carries unique design changes that must be traceable, there is the further difficulty of maintaining a list of hull-applicable piece parts. Visualization systems have, in their short history, been focused on design data. Changes need to be made to accommodate multiple product structures and bill of materials. MRP systems may also need to be enhanced in order to carry associativity at the piece part level from construction parts back to source CAD data.

Visualization on the shop floor

The shop floor and shipyard environments have typically enjoyed limited support for advances in computer hardware and information services. The past decade has seen a revolution in information processing on the design floor, both in computer hardware and software. Similar advances have not been carried through to the operations facilities. The use of visualization software with improved computer hardware in manufacturing areas has many useful applications. Display of assembly sequences can be used for verification of construction planning and for pre-start familiarization by work crews. Visualization linked to underlying MRP and PDM data can be used as a means of performing queries for necessary manufacturing information. Ultimately the 3D model displayed on a computer could be used as the paperless shop to eliminate the need for printed drawings.

Distributed desktop visualization

The visualization systems in use today for ship design make use of dedicated computer hardware that is exclusively tied to either the CAD system or the visualization system. These are special purpose computers that are used only for design creation and design review. Historically these dedicated computers were required in order to provide the necessary processing power to render large arrangement models in 3D. Today standard desktop PCs are adequate to handle visualization of reasonably complex arrangements. However, the standard PCs in use throughout the ship design organization often do not have network access to the visualization data and do not have viewer software. The monolithic visualization systems that were based on dedicated hardware need to be adapted to a lightweight distributed environment. Modifications may need to be made to enable viewing of smaller area breakdowns to account for less capable hardware. Ease of use and ease of data access will also need to be addressed as the user base changes from dedicated expert users to more novice and casual users. The overall review process may also need to be changed to take advantage of the widespread, immediate access to the ship design data.

III. Integration Strategies and Technologies

1. Systems technology requirements in the shipbuilding industry

Regardless of the size of the ship, the shipbuilding product life cycle typically takes the form illustrated in Figure 3. There are four major stages in the life cycle. For simplicity, Figure 3 represents a waterfall process, but in reality the shipbuilding process is iterative at virtually every stage. Nevertheless, the waterfall model does shed some light on the relationship between adjoining process steps. Typically, each major process step results in a handoff to the next step. The handoff is comprised of the information deliverables, the product model work products, that are used as the basis of the next process step. The subsequent process step refines the product model. The new model adds new information and new value. The block arrows in Figure 3 represent the handoffs. Despite the separation, no process step is independent of its predecessor.

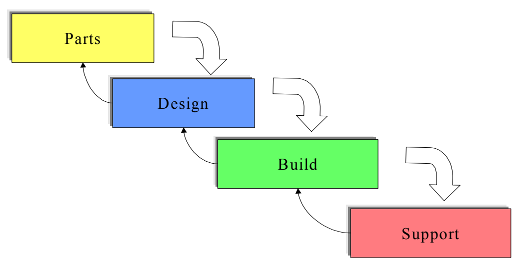

Figure 3: Shipbuilding Product Life Cycle

Each stage in the product life cycle is comprised of a number of smaller processes. The pattern of hand-offs and dependencies is repeated even at the sub-process level. This pattern applies at all levels and within all stages of the product life cycle, and it provides an insight into the shipbuilding systems technology requirements. The shipbuilding product life cycle is a complex process flow in which each activity iteratively feeds a refined product model as the primary work product to the next activity, and that activity must maintain visibility into its predecessor's data.

The shipbuilding industry relies on systems technology to satisfy two different requirements: 1) to provide the tools to support each process and 2) to support the interactions between processes. Each major process is supported by one or more application systems. None of these systems is simple to deploy; each embodies its own unique set of technical challenges. However, the real payback from these systems is not realized until they are integrated into a larger "product development environment." There are two approaches available. One approach is to deploy an IDE is illustrated in Figure 4:

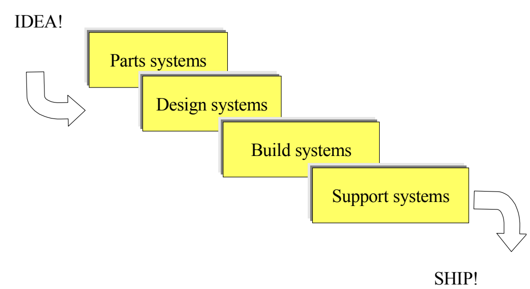

Figure 4: Integrated Development Environment

The goal of the IDE is to integrate the systems within a given shipyard as tightly as possible in order to automate the inter-process hand-off and support interactions. There is a single process flow. One concept initiates the process and defines a class of ship, and the objective is produce and support one or more ships of that class. The requirement is that each inter-process interaction be as seamless as possible. Today the first tier US shipyards are still striving to deploy IDEs to accomplish this goal.

At the same time new business requirements have emerged, and the trend has been toward collaboration among shipbuilders and their industry and government partners. Among Navy programs, major programs are increasingly being awarded to alliances. Collaboration is encouraged, and in some cases unavoidable, between shipbuilders, systems integrators, suppliers, design agents, construction yards, and support organizations. Collaboration is also emerging as a business requirement among commercial shipbuilders. When collaboration becomes a system requirement, the face of the development environment changes drastically. Figure 5 illustrates an Interoperable Collaborative Development Environment (ICDE):

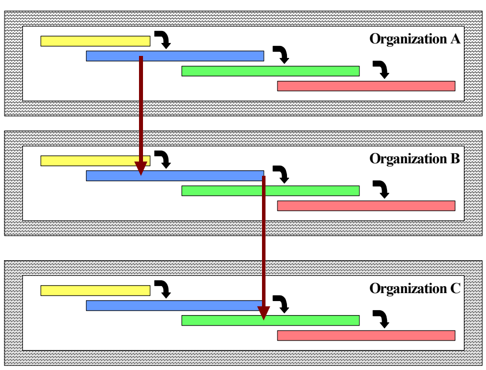

Figure 5: Interoperable Collaborative Development Environment

The ICDE differs from the IDE in that the inter-process handoffs may now cross enterprise boundaries as well as system boundaries. The ICDE must be designed to accept a handoff from some other ICDE at any point in the product life cycle. For example, two companies may share the design of the major components of the propulsion system of one class, or one shipyard may be the construction yard for a ship that was designed elsewhere. This requirement puts new constraints on the technology associated with each hand-off. Seamlessness is no longer the overriding goal to be attained at all costs. Now the goal is openness. The ICDE must minimize the burden on its downstream team members. Moreover, recent advances in information technology have made it feasible to use this approach for tool integration within a single shipyard as well.

2. Matching technologies to requirements

Today there are two leading families of systems technologies: component software for distributed objects and information interoperability. Shipbuilders are very familiar with the concept of components; a ship is essentially a composition of components, and the more standard components can be used, the more cost-effective the ship. In fact, standard components are well established and well understood in most engineering disciplines. However, until recently components have been unsuccessful in the world of software systems. A software component is a piece of software that is independently produced, acquired and deployed. It interacts with other software components to form a functioning system. Composite systems composed of standard, re-usable software components are called *component software.* Component software is a key enabler for system building. This technology represents the first alternative for systems integration.

Component software is closely allied with distributed object technology. Today there are three major competitors in this space: Microsoft's DCOM, CORBA C++ and Enterprise JavaBeans. This technology is high-tech with a high cost of entry; it is a technology "for the elite". In its enterprise form it can be afforded and supported only by large enterprises. It is behavior-centric. Its primary purpose is the building of systems, that is, the implementation of tools that can create, manage and modify the work products of an enterprise. It is highly dependent upon a particular technology infrastructure.

The current direction in the U.S. shipbuilding industry is leaning heavily toward a dependence upon component software and the system vendors that have adopted it. This approach makes sense with respect to the system building requirement. However, it is seriously flawed as a solution to the systems integration requirements of the industry.

At the other end of the systems technology spectrum is information interoperability. Information interoperability is the ability for all stakeholders to link to and access information dependent of the platform or technology that owns and manages the information. Information interoperability is the interchange of information across information boundaries, including technology, organizational, system and computer process boundaries. It involves the pervasive use of standards. Information interoperability and component software can work together, but as we will see, they represent essentially different technologies. Information interoperability is a key enabler for the integration of systems into a product development environment.

Without going too deep into the details, each technology has certain characteristics that must be considered in order to apply the technology to requirements profitably. Information interoperability is centered in the Internet world. Its standards are developed and adopted by the World Wide Web Consortium (W3C), and its base is the XML family of technologies. The technology is low-tech with a low price of entry. It is a technology "for the masses"; vendors target a high-volume, low cost market. It is information-centric. The metaphor in the XML world is the document. This technology seeks to make information availability its top priority. Simplicity is central to its philosophy. For example, XML became successful by restructuring an existing technology and providing 80% of the functionality with 20% of the complexity. XML is designed for technology independence. The rule of the Internet is that one can never be sure what kind of computer or system is on the other end of the network.

3. Enterprise Application Integration with XML and Web Services

Five years ago, the only technology options available for enterprise application integration were the component software/distributed object technologies. These technologies had the drawback that they were complex and carried considerable overhead. As a result, they were only available to enterprises that had substantial information technology resources. Each distributed object technology required its own team of experts making integration across technology frameworks very difficult. Since that time, Web technologies have matured to the point that most shipyards support an Intranet infrastructure and know how to deal with and maintain Web servers and associated support tools. Moreover, the standards for data sharing using XML have advanced to the point that tools are now widely available to process and manipulate the XML data that would be the core of such a systems integration infrastructure. Early efforts at building CIM (computer integrated manufacturing) frameworks were frustrated precisely by a lack of such an infrastructure. The first proponents of this approach found that they had to devote most of their resources to putting the underlying enablers in place. These enablers included such basics as security, access control, data translators, directories, query and search engines, presentation services, and inter-system messaging. With this approach, the entire integration problem became bogged down in software development issues. Nothing could be accomplished with software programmers, and when a system was in place it was limited in extensibility and re-usability. The landscape has changed with the advent of Web and Web services technologies. Now much of the infrastructure is already to the shipyard via its Intranet foundation. Database vendors are providing tools to make XML data directly available through the Web servers. Tools are in place so that information interoperability can be accomplished largely by means of configuration files – many of which can be created and maintained by shipyard personnel themselves.

The issue of system integration is especially important for the support of production processes. Apart from their own interactions, production processes rely heavily on information that is created and managed within the ship design systems. This information includes the complex product model data that ultimately must be translated into instructions that can be understood by a tradesman or into CNC code that can drive the manufacturing process. The single, monolithic system approach has become an inhibitor to progress within production processes. This approach is still being advanced by major ERP systems vendors such as SAP and by the major CAD/PDM vendors. However, the shipbuilding industry should begin to assert its prerogative for more modular systems supports. The software industry is moving rapidly to embrace the Web services architecture. In this architecture, software services are presented in modular and interoperable form that can be composed to accomplish more complex ends. Moreover, the system infrastructure that supports the integration is built upon Web and Intranet technologies that are already widely supported within the shipyards and which are simple and economical enough that they can be used by small and medium-sized enterprises as well. By adopting this approach, the shipbuilding industry also needs to re-examine the role of software outsourcing. There should be an effort to restrict outsourced software services to infrastructure support and to minimize (or eliminate) the need for application development. The Web services architectures, especially the use of XML for information sharing, enables the use of configuration files and scripts to fine-tune and customize systems and system integrations. The shipbuilding industry should begin to position itself so that its own personnel can accomplish these customizations. This represents a change not just in technology, but also in the culture.

4. Strategy for information interoperability

Systems integration by means of information interoperability is the key enabler for potential savings among shipbuilding production processes. The information requirements for the shipbuilding production processes are quite similar for all shipyards, defense as well as commercial. Moreover, co-production between shipyards presents a key opportunity to maximize productivity. In some programs the sharing of work is contractually required; in other programs, such a sharing of work is the best means to improve efficiencies in cost and schedule. Co-production makes it possible for a program to best exploit the core competencies and other advantages of different shipyards. Co-production provides the opportunity for defense yards to more cost-effectively support customer requirements. It also provides the opportunity for commercial yards to share in some aspects of defense shipbuilding.

Current initiatives such as the NSRP systems technologies projects (ISE, SPARS, ISPE), the DoN XML repository and the Navy ERP initiatives are addressing the problem by defining information standards and infrastructures for the sharing of shipbuilding data. Unfortunately, there is a non-technical obstacle to the full implementation of this information sharing approach. In many cases the information is more valuable to the receiving yard than to the sending yard. The sending yard of the information is typically under contract to provide the information, but in most cases it does so in the easiest way possible. There is no cost incentive for the sending yard to devote its own resources to make the information easier to use by the receiving yard. In the design arena, a similar calculation applies to the CAD/PDM vendors. Most CAD/PDM vendors are eager to import data from other systems into their own environment, but they are less enthusiastic about making their own data available for use in competitors' systems.

The architecture for information interoperability among shipbuilding systems should utilize the concept of data mediation and should be constructed around a global data broker capability. The global data broker is a central medium to leverage software applications and data to accommodate the myriad of databases and data processing methodologies being managed by various communities' shipbuilding production processes. The challenges, both technical and cultural, are similar to those encountered in recent attempts at enterprise application integration (EAI). While enterprise application integration presents obstacles that have still not yet been fully overcome, global information interoperability represents even greater challenges. It is helpful to consider global information interoperability in light of the lessons learned in enterprise integration. Each process stage has its own mission to accomplish. Access to a store of information is typically an essential part in accomplishing this mission. Each process stage deals with two kinds of information – the information that it creates and manages for its own ends and the information that it receives from other processes.

Some of the information created by the process team is private and of no use outside the team, but some of the information supports the missions of other teams and must be made available to those authorized to use it. Within the typical enterprise today, the information systems of each organization consist of a diversity of computer platforms, middleware technologies and database management systems. Each organization devotes most of its wherewithal to the accomplishment of its own mission. Its private information is, thus, optimized to capture the information requirements appropriate to that mission. In the global arena, this situation is exacerbated. It is unrealistic to expect that a team will sacrifice its own mission to support the needs of global interoperability, which by their very nature are constantly evolving and can never be fully known in advance. Even in today's enterprises most information exchange occurs by means of hard-coded, point-to-point solutions, each highly dependent on the technology used for the integration (and sometimes on the technology used in the legacy systems themselves). The end result is a rigid infrastructure, which can be extended only at great (and often prohibitive) cost.

A salient lesson from current EAI endeavors deals with the support of the system after deployment. A system that is tightly coupled to particular technologies can become too brittle to be maintained in the face of the change that is inevitable. This is a valuable lesson for the architecting of the global data broker; however, before it gets to that point the global data broker must first solve the problems associated with widespread deployment. Major enterprises have enough central authority to deploy a manageable subset of enabling technologies. There is no such central authority for the global data broker, which can be realized only after a sufficient set of enabling technologies have achieved world-wide adoption.

The functional requirements for the global data broker are roughly equivalent to the functional requirements associated with enterprise integration; however, the non-functional requirements are significantly different, and the result is that current EAI technologies are not completely satisfactory for the global data broker. Some of the key non-functional requirements of the global data broker are that it must:

– maximize the autonomy of the participating teams
– be built on widely-adopted, open standards
– be maintainable in the face of change and incomplete requirements
– assure the protection of the information and information infrastructure of the participating teams
– be modular in design

The cost of entry for a participating team must be low enough that accommodating the needs of the global user community does not jeopardize the ability to meet its own private needs. The cost of participation must be substantially smaller than the benefit from participation (because the benefits are often seen as intangibles without quantification). In practical terms, this means that the global data broker must make it as easy as possible for a team to join and to participate. This means that the global data broker must, on the one hand, accommodate the semantic differences between different teams' systems; and, on the other hand, it must hide all syntactic differences. The global data broker must be capable of hiding implementation differences at every level – from the information syntax to the underlying data model to the query language. In other words, the global data broker must be free from any tight coupling to or reliance on any particular implementation technology.

It is important to resist the temptation to adopt critical enabling technologies that are proprietary or closed. This temptation is especially strong if a proprietary technology offers some unique discriminators or, worse, if the alternative is no implementation at all. In fact, the global data broker should not be deployed until the complete set of enabling technologies has been widely adopted as open standards, with multiple vendor support. This is the unique opportunity for the global data broker. The recent emergence of the family of Web and XML standards marks the first time this requirement has been satisfied.

The global data broker must be maintainable. It must be relatively easy to extend the infrastructure to adopt to change instigated by new functional requirements, new supporting technologies, new platforms, new combinations of participating communities

Background: fusion or mediation - The need for information interoperability has long been recognized. Since the early 1990s there have been two predominant architectural approaches: fusion and mediation. Most early EAI strategies focused on the *fusion* approach: the definition of a single organization-wide schema. Early implementations of the approach typically took the form of a single database management system that was accessible to all users within the organization. Driven by the need for data access with the organization, these efforts did not address the needs of users in other organizations. The technology supported the closed approach, and it was possible to accomplish the job at hand. No technology existed for a more open solution, and the price of integration was too high.

Eventually the need for enterprise-wide integration became apparent – usually after a number of organization-wide systems were in place. The first thought in many IT organizations was to expand the fusion approach to the enterprise level. This demanded the definition of a single global schema for the enterprise, which was often attempted by the implementation of single database management system. The thought was that the same approach that worked within an organization would work across organizations. Moreover, there were still no other viable alternatives.

Yet there were serious issues with the fusion approach as an enterprise integration tool. It necessitated the replacement of local databases as well as the migration of existing applications to the new database. Some enterprises were willing to make this leap and they found new problems. The migration of legacy systems is a costly process, demanding the expertise of professional programmers and database engineers. The most daunting problems, however, had to do with managing change, given the resistance of the fusion approach to change. In most large enterprises process re-engineering is continuous. Application requirements often change independently of integration requirements. Moreover, with the tight coupling of the first deployments every change in technology or implementation upgrade precipitates changes in the deployment. The tight coupling of every application to the enterprise schema makes local change painful and disruptive. What's worse, many enterprises had already adopted a COTS strategy with respect to software, and they lacked the ability to modify these applications.

The single system (data warehouse) variant of the fusion approach reaches its limit in enterprise-wide integration. For the challenge of inter-enterprise integration, the technical barriers are insurmountable. The technology itself breaks down – it is not possible to deploy a single DBMS or even a single middleware technology across system domains such as those imposed by enterprise firewalls. Moreover, participation in an inter-enterprise integration demands a degree of local autonomy not realizable with the fusion approach.

An alternative architecture for information interoperability is *mediation*. The idea is to employ the principle of federation. The autonomy of local systems is maximized, although each local system surrenders a small amount of autonomy in exchange for the benefits of integration. The goal of the architecture is to make the couplings in the system as loose as possible, that is, to remove all accidental couplings – platform, programming language, middleware technology, query language, even the data model itself. The crux of the mediation objective is to deliver information to the user in a form that is usable to him regardless of the form or location in which it is stored. Consequently, the key enablers of the mediation approach are transformations, both of the information itself and of the queries that guide the access to the information.

Having committed to maximizing the autonomy of the local data sources, the burden now falls on the technology to solve all the inhibitors to autonomy, and there are many. The utilization of mediation to achieve information interoperability demands that each technology enabler not only be efficacious but also widely accepted and widely adopted. Early implementations of the mediation architecture have proven technically feasible, even successful; however, they have not met with widespread adoption because they have relied on enabling technologies that render the solution as closed as the fusion approach. A mediation architecture built upon the ODMG standards for object databases and object query language has been proved to work, but its potential adoption is limited to systems that embrace that technology. Until recently the list of technology gaps that precluded the use of mediation was quite long:

- a universal syntax for the representation of information
- a common query language
- a messaging capability, including the means to deliver messages as well as an open format for the message payload
- a technology independent means for specifying interfaces
- a widely implemented information modeling language

The lack of technology support in any one key area disqualifies mediation as a serious contender as a solution for the global data broker. Finally, the deployment of the mediation architecture in relatively closed environments has obscured a number of second-generation inhibitors. For example, mediation is often presented as an alternative to the fusion approach when, in fact, mediation cannot work without an implicit global schema of its own. The global schema used for mediation is subtly different from the global schema used for fusion, but many of the technical issues that need to be addressed can be understood best in light of experience with fusion methodologies. The global data broker, then, depends upon a new approach, a synthesis of fusion and mediation

IV. Prioritized Development Roadmap

This section summarizes the opportunities for improving production processes by means of new systems technologies. It is presented in the form of a development roadmap. The specific opportunities are described in detail in the sections above. In this section the opportunities are presented as tasks that are grouped into related categories. The categories are prioritized. The three categories are:

Deployment of a complete product modeling capability – It has been the intention within the shipbuilding industry for the past decade to exploit the benefits of a product model. There have been considerable gains in a surprisingly short period of time; however, there is no capability among US shipbuilders to create, manage and share a complete product model. There are gaps in all stages of the shipbuilding life cycle. This report enumerates only those that are related to production processes (directly or indirectly). Moreover, there are some areas that have only begun to be addressed. In particular, new systems technologies in the area of accuracy control have been deployed mainly as standalone capabilities. The full benefits of these capabilities will only be realized when the requirements that they generate are added to existing CAD and CAM capabilities.

Adoption of modular, interoperable systems – Because the shipbuilding functional requirements are so demanding, the industry has always been pushing technology providers to their limits. Until now there has been little opportunity to select among technology providers on other than functional criteria. The major systems technology investments have been in monolithic systems that maximized available functionality. With today's technologies starting to change, technology offerings can now be evaluated on the additional, non-functional criteria, such as modularity and interoperability. Over the past decade the shipbuilding industry has had the opportunity to experience the difficulties associated with monolithic systems. Although it may be possible to deploy such a system and satisfy the specific functional requirements of a business process, it has proved very difficult to integrate these systems with other systems within a shipyard. Interoperability across organizations is limited, and it is very difficult to modernize such systems. The result is that many shipyards are forced to maintain functioning systems because the cost to replace such a far-reaching capability is prohibitive. Previous investments in customized integration with the system are not easily abandoned. With today's technologies it is becoming possible to select COTS systems based on their modularity and interoperability. Most systems vendors are moving toward Web-based and component-based technologies.

New functional capabilities – In addition to the fundamental changes described above, there are a large number of specific applications that could be developed somewhat independently. This category is somewhat of a catchall for those capabilities.

These categories have been described in the order of proposed prioritization. The rationale for this prioritization is different from that found in shipyards nowadays. Today the most typical strategy for prioritization is to go after the low-hanging fruit first. There may be some justification for this in an individual company – to get the quickest return on the smallest investment and lowest risk. However, this approach does not work well for the industry as a whole. In the systems technology arena many of the potential benefits are interdependent – originating from the basic notion of improving efficiency by creating a re-usable model of the product. The completion of the shipbuilding product model is the first priority. It is a pervasive undertaking. It entails a number of parallel activities – including influencing the major systems vendors (CAD, CAM, PDM, ERP, etc). It entails coordination across domains – CAD systems must capture the necessary information to support manufacturing requirements; CAM systems must capture the necessary information to support accuracy control requirements. Even in advance of this stage the shipbuilding industry as a whole needs to agree upon those information requirements. This activity is complicated by issues of competition and by the sheer magnitude of such a collaboration. The work has already begun in the STEP arena but it must be significantly expanded as described in the items listed below.

The second priority is the adoption of modular and interoperable systems. This set of tasks is particularly hard to sell because the benefits are perceived by some as intangible. The shipbuilder, who easily recognizes the benefits of using standard parts to build a ship, does not always recognize the advantage of using standard software or data components. However, the benefits from this approach are almost as far-reaching as the benefits attributable to a complete product model. Most of the essential functions required for ship design and construction are supported by available systems. What is missing is the ability to continuously improve these systems. For this to happen the systems themselves need to be modular (small enough to be replaced without prohibitive cost and available from more than one vendor) and interoperable (able to share inputs and outputs with the other shipbuilding systems). These activities can be seen as the final step in the re-use of the product model. Once a complete product model has been constructed, it still remains to share its benefits with other users.

The final priority items are those that represent independently developable functions. It should be straightforward to obtain these capabilities; however, their benefits are circumscribed and do not extend beyond the process at hand.

The following is the prioritized roadmap. Each line item corresponds to an opportunity that is described in one of the sections above. The section is in parentheses.

PRIORITIZED ROADMAP

Deployment of a complete product modeling capability:

(CAD) CAD/PDM system enhancements (e.g. instance management)
(CAD) Feature-based design
(Product model) Digital product specification
(LOFT) Feature-based design product models
(ROBOTICS) Integration with the design process
(ASBUILT) Matching inspection features with design features
(ASBUILT) Improved means for processing critical dimensions
(ERP) As-built and as-maintained product models

Adoption of modular, interoperable systems

(CAD) CAD/PDM data sharing
(LOFT) Improved interface to accuracy control systems
(LOFT) Move away from obsolete data formats
(LOFT) Better support for inter-company data sharing
(LOFT) Improved interoperability with ERP data
(LOFT) Decoupling CAD and CAM data
(NEST) Improved integration with ERP data
(NEST) Part identifiers for accuracy control
(PIPE) Standard CAD/CAM exchange format
(SHEET) Standard CAD/CAM exchange format
(ROBOTICS) Improved software tools
(ROBOTICS) Interoperability and standard data formats
(ASBUILT) Standards for the interoperability of as-built data
(ERP) Modular ERP capabilities
(ERP) Interoperability of ERP and life-cycle support systems
(VIZ) Data management and integration with design PDM
(VIZ) Integration with MRP and construction data
(PM&S) Standard for process data definition
(PM&S) Process knowledge and management

New functional capabilities

(LOFT) Product data management for CAM (lofting) data
(LOFT) Automation of lofting process
(PIPE) CAD/CAM rules checking
(PIPE) Automated planning
(PIPE) PDM capabilities for configuration management
(PIPE) Interference checking
(ROBOTICS) Changes in construction planning and scheduling
(ROBOTICS) Cutting and material preparation
(ROBOTICS) Reuse of skill and knowledge resources
(ROBOTICS) Specialized techniques for thick sections
(ASBUILT) Product data management for as-built data
(ASBUILT) Specialized inspection tools
(ASBUILT) Feature recognition from point clouds
(ASBUILT) Visualization tools
(ASBUILT) Build to fit/reverse engineering
(PM&S)/(Lean) Ease of use – Process Mapping
(RP) Dynamic interference checking

(VIZ) Visualization on the shop floor
(VIZ) Distributed desktop visualization

Recommendations

Based on this report, further research should be planned in the areas of opportunities outlined in the above roadmap. The major stakeholders should be involved with reviewing the areas of opportunity and translating them into an action plan. This action plan could be similar to the Strategic Investment Plan (SIP) published by NSRP. This new strategic plan could then be used to help direct future research announcements and project selections.